A Tool to Support the Planning of Ground Delay Programs Subject to Uncertain Arrival Capacities

by Michael John Hanowsky

B.S., Industrial Engineering and Operations Research
University of California, Berkeley, 2000

SUBMITTED TO THE DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING AND THE SLOAN SCHOOL OF MANAGEMENT IN PARTIAL FULFILLMENT OF THE DEGREES OF

MASTER OF SCIENCE IN TRANSPORTATION
AND
MASTER OF SCIENCE IN OPERATIONS RESEARCH

AT THE MASSACHUSETTS INSTITUTE OF TECHNOLOGY
JUNE 2006

Signature of Author..
Department of Civil and Environmental Engineering
April 1, 2006

Certified by..
Amedeo Odoni
T. Wilson Professor of Aeronautics and Astronautics
Professor of Civil and Environmental Engineering
Thesis Supervisor

Accepted by..
James B. Orlin
Edward Pennell Brooks Professor of Operations Research
Co-director, Operations Research Center

Accepted by..
Andrew Whittle
Professor of Civil and Environmental Engineering
Chairman, CEE Departmental Committee for Graduate Students

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Submitted to the Department of Civil and Environmental Engineering and the Sloan School of Management on April 1, 2006 in Partial Fulfillment of the Requirements for the Degrees of Master of Science in Transportation and Master of Science in Operations Research

ABSTRACT

A prototype tool was developed to support the planning of ground delay programs (GDPs) under uncertainty. Planned hours in advance, GDPs are subject to significant arrival capacity uncertainty, which reduces their efficacy in defraying the high cost of airborne delays. The tool addresses this uncertainty by using a set of different possible arrival capacity profile forecasts and modeling the outcome of the program under each forecast. A variety of different metrics are developed based on these results, including both system-wide and flight specific forecasts of queue size and the evolution of delay over time. To allow air and ground delay to be considered simultaneously, a cost function that takes both into account is proposed.

The tool also addresses the dynamic nature of a GDP by allowing the traffic manager to set a system time variable and model possible future decisions. Taken a step further, these projections can be used as part of a two-step model, which evaluates a program under the assumption that a traffic manager will revise the GDP at a later time, once additional information regarding arrival capacity forecasts has become available. Revising a program can significantly reduce its expected cost, but different programs may not respond in the same way to future revision and are likely to exhibit differing magnitudes of expected cost reduction. In fact, the best initial decision may be one that trades initial cost for the ability to revise the program more effectively in the future.

Thesis Supervisor: Amedeo Odoni
Title: T. Wilson Professor of Aeronautics and Astronautics and Professor of Civil and Environmental Engineering

BIOGRAPHY

Michael Hanowsky is a doctoral student in the Engineering Systems Division at the Massachusetts Institute of Technology. His research focuses on the air transportation industry with an emphasis on operations research methods, risk, and uncertainty. His interest in transportation is rooted in a fascination with the role that large-scale infrastructure plays in society, especially in the developing world. In addition to his academic pursuits, Michael is a strong believer in the role of the community and has served his communities in various roles, most recently as the graduate student representative to the Institute Committee for Parking and Transportation Issues at MIT.

As an undergraduate, Michael received a Bachelor of Science degree from the University of California, Berkeley (2000) in Industrial Engineering and Operations Research, with a minor in Business Administration. While at Berkeley, Michael worked for the Sierra Club, sold computer software, and affixed rear make and model emblems to Toyota Corollas (model year 1999). Michael was also president of the departmental honors society (AΠM) for Industrial Engineering, a football fan, and the sixth seat on the Berkeley racquetball team. In Boston, he has had to take up squash for lack of a racquetball court. The jury is still out.

Before coming to Boston, Michael also worked in Chicago as a consultant for the pharmaceutical industry, with a particular expertise in marketing issues and sales force management. He has also traveled extensively and is extremely curious about other people and cultures.

Michael hates talking about himself in the third person. Most of his friends call him Mike.

ACKNOWLEDGEMENTS

First and foremost, I want to thank Rick Oiesen and Dr. Eugene Gilbo at the John A. Volpe National Transportation Systems Center in Cambridge, MA. Their time and effort helped me to understand how the FAA designs, considers, and implements ground delay programs – invaluable assistance that provided the foundation for all of the work contained in this thesis. It is because of Rick and Eugene that I have a great appreciation for the difficult decisions made every day by air traffic managers.

I would also like to thank my advisor, Prof. Amedeo Odoni. This thesis was very much a learning process, both about ground delay programs and also about the very nature of research and it would not have been possible without his guidance, support, and patience. He deserves my gratitude not only for his help on this particular document, but also for teaching me how to think about research and academic writing in general – a lesson that will stay with me long after the ink has dried.

There are many others whose support I so greatly appreciated over the last few month (though, at times, I'm sure it might not have seemed that way), especially my parents and sister, who put up with my melancholic writing during the family vacation! And to each and every one of my friends, whose kind words, phone calls, letters, lunches, trips to Fenway, unannounced visits, and occasional recipes helped me redouble my efforts and provided such necessary distractions during some very difficult stretches. Your support meant and means a lot to me!

TABLE OF CONTENTS

TABLE OF ILLUSTRATIONS

Chapter 1:

Chapter 2:

Chapter 3:

TABLE OF ILLUSTRATIONS

TABLE OF ILLUSTRATIONS

TABLE OF EQUATIONS

TABLE OF EQUATIONS

Chapter 1: Introduction

Increased air traffic congestion in the airspace around airports and a corresponding increase in the amount of airborne flight delays pose a significant cost to the aviation industry. One technique of managing the flow of aviation traffic, a ground delay program (GDP), is designed to reduce the high fuel and safety costs of airborne delays by, instead, delaying flights on the ground before their departure. To reap this benefit, however, GDPs must be planned well in advance of anticipated congestion, due to the flight time required en route between a departure airport and the location of expected delay. As a result, GDPs are often implemented before full knowledge of a future situation, including the weather conditions at the destination airport, is available, which reduces their efficacy in lowering the cost of delays. This thesis is motivated by opportunities to improve the information considered in the process of designing a GDP and, as a result, reduce the high costs of air traffic congestion.

Recent advances in weather forecasting technology suggest that a new type of probabilistic weather forecast may soon be available for congested airports. To incorporate this new information, this thesis proposes an analytical tool that can be used to evaluate a proposed GDP for an airport with uncertain arrival capacity. Chapter One introduces important concepts; identifies the stakeholders in air traffic flow management; and outlines the motivation, approach, and contributions of this thesis. Chapter Two discusses GDPs in greater detail, including the information that is currently used to design a program. Chapter Three illustrates new metrics that are derived by the tool when uncertainty in airport arrival capacity is considered. Chapter Four details the calculations, models, and assumptions behind the tool. The conclusion, Chapter Five, summarizes the key contributions of this thesis and suggests questions for future research.

Section 1.1: The Federal Aviation Administration

The air transportation industry in the United States has grown significantly in the past 20 years. Deregulation of commercial air services, changes in the business environment, and new materials and manufacturing technologies have led to a greater number and variety of aircraft in the skies than ever before, from the proliferation of small corporate air taxis to the use of the much-publicized Airbus A-380. Industry growth has also led to increased congestion in the skies, where aircraft compete for limited airspace around busy airports. Despite the increase in air traffic, however, air travel has never been safer. This safety record is largely due to the oversight of the Federal Aviation Administration (FAA[1]), which regulates the use of the National Air Space (NAS) of the United States.

The primary mission of the FAA is to provide for the "safe and efficient use of navigable airspace,"[2] which is promoted through the agency's involvement in many aspects of the air transportation industry, including licensing of pilots and air carriers, oversight of aircraft maintenance, assistance in airport planning and development, and management of the NAS. Of

[1] The European counterpart to the FAA is EUROCONTROL
[2] http://www.faa.gov/about/mission/activities (August 1, 2005)

these duties, the FAA is best known for its role in the management and control of aviation traffic, Air Traffic Management (ATM), which can be divided into two components: strategic air traffic flow management (ATFM), the management of large groups of flights in response to changes in the NAS, and tactical air traffic control (ATC), the detailed routing and spacing of individual aircraft both en route and on the ground. For example, to respond to severe weather fronts, the FAA exercises both types of air traffic management: strategic control to select preferred routes onto which to divert aircraft around a storm and tactical control for the specific instructions given to flights to use an ordained route and maintain a safe distance from other aircraft.

Air traffic management is administered by a hierarchy of traffic control centers, with a single facility, the Air Traffic Control System Command Center (ATCSCC), in Herndon, VA, that manages and coordinates strategic responses to nation-wide air traffic issues. In the second tier, geographically-distributed Traffic Management Units (TMUs), each located at one of the 21 Air Route Traffic Control Centers (ARTCCs)[3], address regional, strategic air traffic flow management decisions. At each of the TMUs, traffic managers (TMs) are responsible for making strategic decisions in coordination with TMs at the ATCSCC. As the third tier of control, air traffic controllers interact with individual flights and are responsible for individual sectors within each segment of the national airspace. These controllers make tactical decisions for en route, approach, and ground-based aircraft movements. Together, the three ATC tiers are responsible for the safe, efficient, and coordinated movement of aircraft within the NAS.

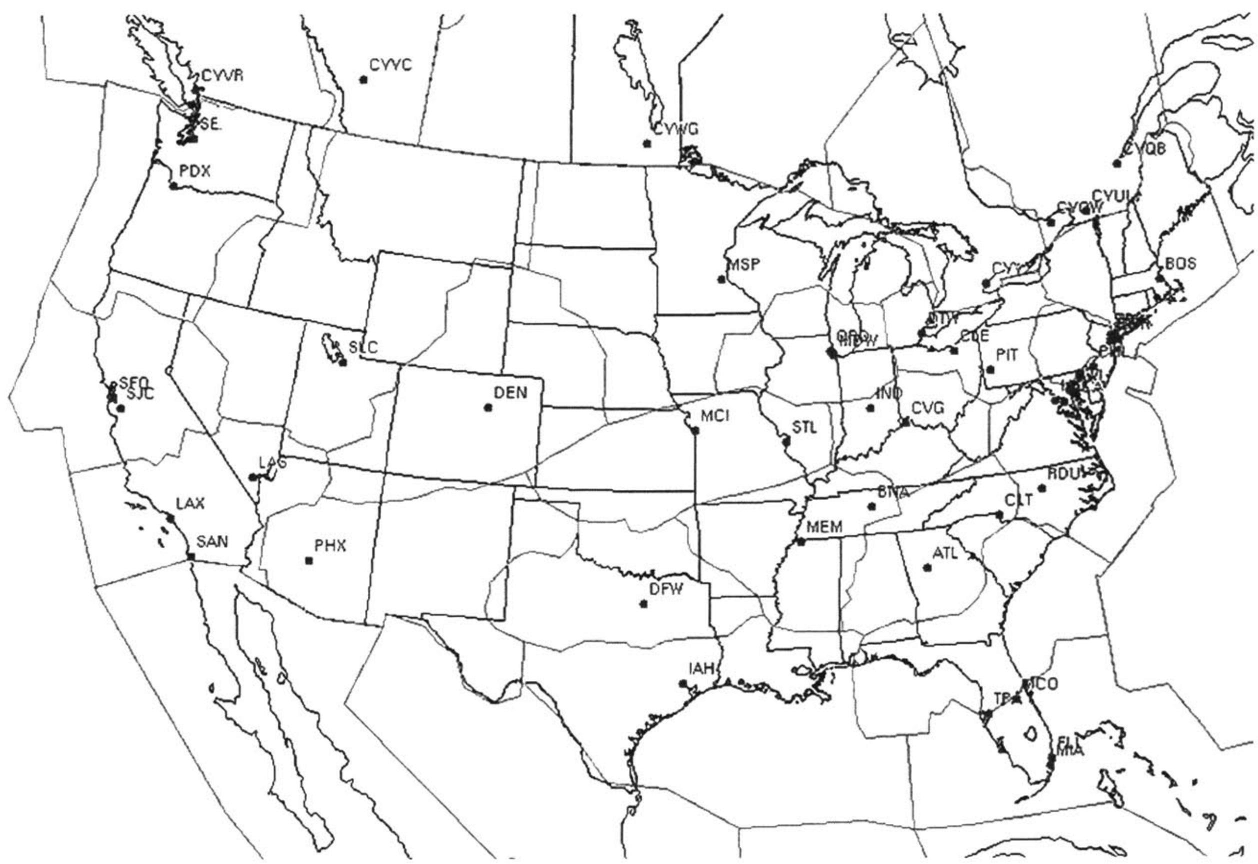

Figure 1-1: Map of the U.S., including major airports, with super-imposed standard ARTCC boundaries
Source: Traffic Situation Display software; adapted using Adobe Photoshop

[3] 20 ARTCCs are located in the continental U.S. and 1 in Anchorage, AK

Section 1.2: Airborne Delays

Air traffic control is especially important around busy airports, where there is a high concentration of aircraft in the air and on the ground. To provide for safe operations, the FAA requires a minimum separation between aircraft at all times. When applied to aircraft during the landing approach, this required separation results in a finite arrival capacity, i.e. in a limit on the number of landings (dependent on the type of aircraft and atmospheric conditions) that can occur at an airport during a period of time. The number of landings, or arrivals, over time is often referred to as the arrival rate.

Aviation regulations provide all qualified aircraft with the right to request to land at a civilian airport at any time, such that more aircraft may request to land than can be accommodated by an airport during certain periods of the day. When arrival demand exceeds capacity, air traffic controllers delay flights in the air by establishing an airborne stack, or first-come-first-served (FCFS) queue, for aircraft that request to land. Although airborne queuing treats all aircraft equally, it is highly inefficient and poses both safety and financial risks to air travelers and carriers.

For the purposes of this thesis, the following terms will be used to describe relevant aspects of airport and ATM operations:

- Arrival Time: The time at which a flight lands at the destination airport
- Arrival Delay: Delay of aircraft in the air before arrival due to insufficient arrival capacity at the destination airport
- Demand Time: The time at which a flight reaches the terminal airspace of an airport and requests permission to land
- Arrival Capacity: the maximum number of flights that can land at an airport during a specified period of time
- Stack: An airborne, FCFS queue for aircraft that have requested to land at a congested airport

Section 1.2.1: Sources of Delay

Airborne delays can be anticipated whenever the expected demand for arrivals exceeds the average capacity, even if the period of excess is as short as 15 minutes. As a result, the FAA constantly tracks current and forecasted arrival demand. Although the FAA is not typically proactive in managing excessive demand, at the most severely congested airports, the agency may compare published schedules to a maximum arrival capacity rate (in arrivals/hour) months in advance and request that airlines adjust their flight schedules or reduce the number of flights when more flights are scheduled for a peak period than could land without delay. For example, in 2004, the FAA mandated that American Airlines and Unites Airlines reduce flights at Chicago O'Hare International Airport (ORD) by 7.5%. (Donohue, 2004) However, in addition to being unpopular with the airlines, this approach lacks the precision to avoid many air delays and may also leave some runway arrival capacity unused, wasting a valuable resource already in short supply.

Furthermore, the source of congestion and airborne delay is not always related to demand. During inclement weather, the arrival capacity of an airport may drop significantly when runways are closed or the required spacing between flights is increased. Due to the current NAS load, at busy metropolitan airports, these queues can grow quite large and persist for many hours after the inclement weather has passed and the airport has returned to nominal capacity, resulting in significant delays even when the scheduled number of arrivals at an airport is well within the normal operating capacity. The scenario in Figure 1-2 shows that when weather reduces the capacity of an airport for as little as 30 minutes, delays can persist for hours (represented in the figure as demand in excess of capacity). Furthermore, as weather events can be highly localized and unpredictable, atmospheric conditions cannot be accounted for when flights are first scheduled and must be individually handled by traffic managers. To address airborne delay in the NAS, the FAA must design strategies that can be employed when there is more precise information about the arrival capacity and demand of an airport, when the flights in question are preparing for departure or already in the air.

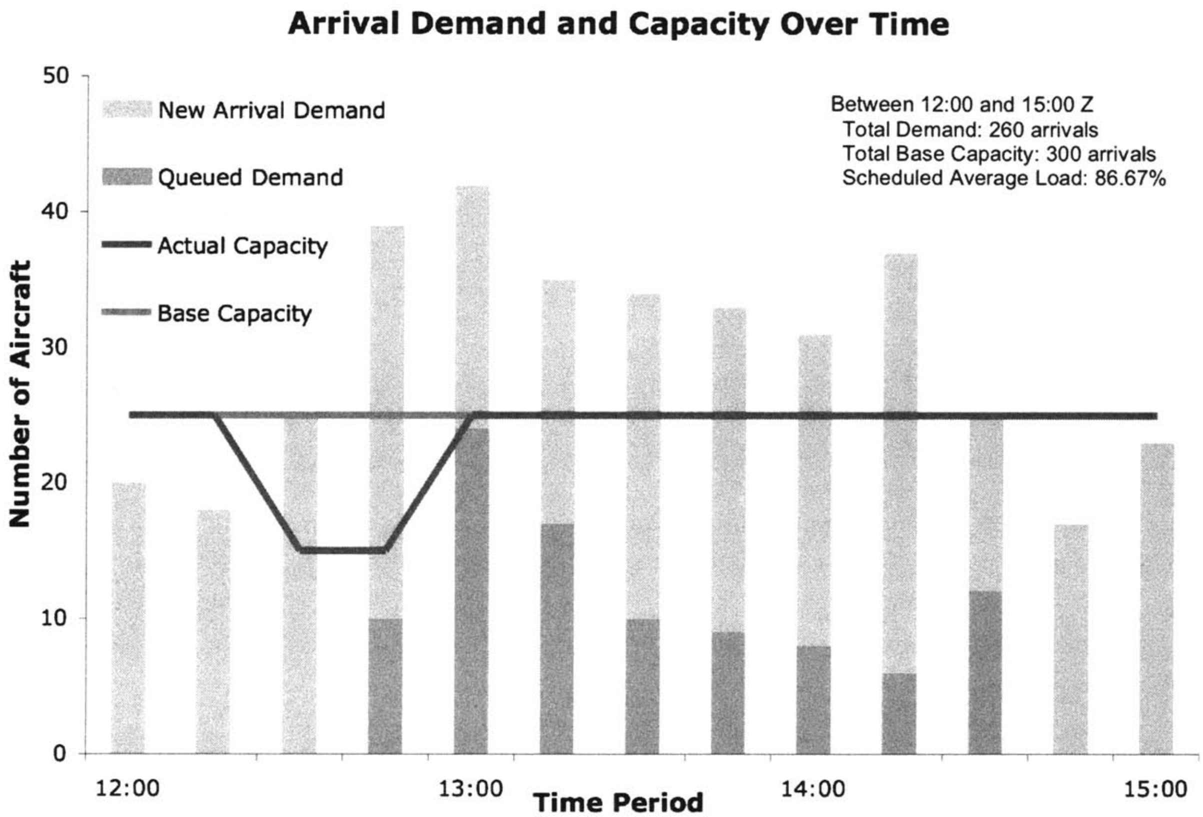

Figure 1-2: Demand for O'Hare International Airport (June 22, 2005) with hypothetical airport arrival capacity profile.
Source: ETMS (June 22, 2005)

Section 1.2.2: Delay Costs

Of primary concern, when it comes to airborne delays, is the question of safety. High aircraft density in terminal airspace increases the workload of individual air traffic controllers who communicate with each of the flights and maintain safe separation distances between them. Increasing the workload of controllers reduces safety; to maintain high standards of safety, the FAA mandates strict limits on the number of aircraft that each controller can be responsible for at any one time.

A second concern is that delays of any type, especially airborne, have large financial costs. The additional flying time incurred by each flight delayed in the air directly increases fuel consumption and flight crew labor costs for aircraft operators. Indirect costs attributed to airborne delays include the labor costs for ground personnel and the cost of additional FAA-mandated maintenance checks, which must be performed at prescribed flight-time intervals. Delays also create an opportunity cost for both the aircraft and crew, which, for commercial airlines, are often scheduled to make subsequent flights, and for the passengers and cargo, who arrive late at connecting points for subsequent flights and their intended destinations. As a result of these high costs, delaying flights in the air is a tactical air traffic control response of last resort, used when other anticipatory strategic air traffic flow management (ATFM) techniques are not available. The table in Figure 1-3 lists the different costs of airborne delays to different stakeholders, and their potential responses.

		Response to Increased Costs	
Stakeholder	**Cost**	**Short Term**	**Long Term**
FAA	Air Traffic Controller workload	Tactical and Strategic Air Traffic Management Initiatives	Manage Scheduled Arrival Demand Design New Initiatives
Commercial Airlines	Fuel, Labor, and Maintenance Network Delays Lost Revenues Lost Customers*	Flight Cancellations Flight Diversions Other Network Manipulations (e.g. swapping aircraft)	Increase fares Terminate Scheduled Service
Air Taxi / General Aviation	Fuel, Labor, and Maintenance	Flight Diversions Flight Cancellations	Change Travel Behavior
Passengers	Opportunity of Travel and Time Ticket Cost*	Cancel/Change Travel Plans	Change Travel Behavior
Airports / Cities	Loss of Business Activity*	None	Capital Investment to Increase Arrival Capacity
*Cost related to the response of other stakeholders			

Figure 1-3: Table of stakeholders and the delay costs for each

Section 1.2.3: Air Traffic Control Responses to Delay

Air traffic flow management employs many different strategies and tactics, or traffic management initiatives (TMIs), to deal with airborne delays. In a broad sense, all are designed to reduce the rate at which flights arrive at a congested airport, where delay would otherwise be taken in the air, the most costly form of delay. Some strategies involve delaying flights en route by reducing speeds or redirecting flights onto longer routes. The two most widely applicable strategies are miles-in-trail (MIT) restrictions, which enforce speed limits and prevent passing in the airways leading to a congested airport, and GDPs, which offer the greatest cost savings by delaying flights on the ground before departure but require the most advance planning.

The strategic nature of a GDP makes this response of particular interest in aviation research. Delays assigned by a GDP are calculated so that the revised arrival demand rate will correspond to the availability of runway arrival capacity, alleviating the need for airborne queues and stacking. In essence, GDPs translate air delay directly into ground delay, potentially resulting in savings to fuel consumption and other airborne delay-related costs. However, GDPs must be implemented while flights are still on the ground, often many hours before the anticipated delays will occur. That far in advance, projections of demand and capacity are incomplete or based on information that is likely to change. The time-sensitive nature of a ground delay program results in a large number of tradeoffs during implementation between the ability to act and information on how to act. This thesis will focus on improving the information available to traffic managers to facilitate understanding the tradeoffs associated with a proposed GDP and improve its performance.

Section 1.3: The Value of Information

In planning a GDP, traffic managers must contend with a great deal of uncertainty in the NAS. In the hours between when a program is implemented and the occurrence of the delays it is intended to alleviate, new flights can be added, others cancelled, and the arrival capacity of the airport can change. These changes can have direct impacts on the outcome of a program and present a difficult tradeoff for the traffic manager. Design a program with too much ground delay and available runway capacity goes unused; assign too little ground delay, and extensive airborne congestion results in costly airborne delays. The table in Figure 1-4 indicates types of uncertainty that impact the planning of GDPs and when they are most apparent.

The key to solving the dilemma faced by the TM is information. With perfect information, a TM could design a perfect GDP: all delays occur on the ground, no available capacity is unused, and the program is perceived as fair and equitable to all participants. Without this information, however, a TM must try to hedge against different possibilities by guessing about future weather or by waiting for additional data.

Type	Example of cause	Effective Horizon (hours)
Cumulative Arrival Demand	Maintenance problems cause the cancellation of a scheduled flight before departure	2–12
Arrival Capacity	Inclement weather reduces the number of flights that can land at an airport	0–6
Flight Arrival Time	Favorable high altitude winds allow a flight to arrive earlier than scheduled	0–4

Figure 1-4: Types of uncertainty and when they become important to air traffic control

A principal difficulty facing the traffic manager is that the information and models that assist with the planning of a GDP are of a "deterministic" nature and present only a single alternative about how the program will unfold, even though a large number of possibilities may actually exist. The lack of stochastic analyses is indicative of a lack of stochastic information, such as distributions of flight arrival times, and a lack of consideration as to how such information could be incorporated. In particular, forecast arrival capacities are not available in a probabilistic format applicable to air traffic flow management. Weather is often not known with certainty until it occurs, and traffic managers have only static, deterministic forecasts of capacity upon which to base a program.

The importance of probabilistic capacity forecasts has been well documented in the literature. As discussed in §1.2.1, inclement weather can be highly unpredictable and has a large impact on delays – understanding the different outcomes can lead to significant reductions in delay costs. In practice, most GDP models previously designed have assumed the existence of stochastic weather forecasts. Recent meteorological research has led to the development of probabilistic aviation capacity forecasts with discrete outcomes. This development presents a unique opportunity to explore the possibility of incorporating these forecasts into the planning of a GDP.

Section 1.4: Research Objectives

With the development of new stochastic arrival capacity forecasts for congested airports, this research seeks to explore the use of these forecasts to analyze proposed GDPs. Using an Excel-based tool to model the creation of a GDP, including probabilistic arrival capacity forecasts, this research will address three questions regarding the analysis of a proposed GDP:

1) How can a GDP be modeled to include information about uncertainty regarding arrival capacity?
2) What metrics could be made available to the TM when evaluating a proposed GDP that is subject to arrival capacity uncertainty?
3) How can the dynamic nature of GDPs and the availability of pertinent information be modeled?

Chapter Two will begin with a detailed discussion of GDPs and their formulation.

Chapter 2: Problem Description

In Chapter One, ground delay programs are discussed as a strategic air traffic management initiative to reduce the cost of airborne delays resulting from excess demand at an airport. In application, "excess" demand equally refers to a state of decreased capacity, when atmospheric conditions in the terminal airspace reduce the number of flights that can safely land; additional aircraft form long queues in the airspace around the airport at great expense to users of the NAS. Weather-related events have long been a problem for the design of GDPs. Uncertainty of the timing and severity of anticipated events reduces the cost-control effectiveness of a program.

Chapter Two develops a deeper understanding of ground delay programs and the tradeoffs faced by traffic managers in implementing a GDP. Section 2.1 identifies different air traffic flow management responses to delays in the NAS, with an emphasis on ground delay programs. Section 2.2 discusses the forecasting of airborne arrival delays in the NAS. Section 2.3 narrows the discussion to how ground delay programs, in particular, are designed and the information and specific metrics that are available to traffic managers. Section 2.4 discusses changes to forecasting technologies that motivate this thesis and transitions to Chapter Three, where new, potential metrics are introduced.

Section 2.1: Air Traffic Control Responses to Anticipated Delay

Over short periods of time (minutes not hours), when more aircraft demand to land than can be accommodated at an airport, traffic controllers routinely delay some flights in the air. To maintain the order and safety of the NAS, these delays typically occur at or near the airspace of the destination airport in vertical FCFS queues, called stacks. Aircraft enter the queue at the top of the stack and slowly spiral down, with the lowest flight leaving the stack and beginning the final landing approach. As indicated in §1.2.2, however, the financial and safety costs attributed to stacking are significant and the FAA seeks to, if at all possible, avoid situations where long airborne delays are required.

When future congestion is anticipated at an airport, there are additional responses that traffic managers can use to slow the rate at which additional flights reach the terminal airspace of an airport and enter the stack. One response, metering, reduces the rate at which flights enter the sector containing the congested airport. Although metering can prevent this destination sector from becoming too crowded, it does so by slowing or redirecting – and crowding – air traffic in those sectors immediately adjacent to the airport. For extended periods of delay, metering is of limited use and, in these cases, two, more sophisticated ATFM techniques[4] are employed: miles-in-trail (MIT) restrictions and ground delay programs. The two differ in terms of their ability to reduce the cost of delays and response time to relieve congestion.

[4] A fourth technique, strategic rerouting, is also used, but is similar to metering/MIT from a cost perspective

Section 2.1.1: Miles-In-Trail Restrictions

The first type of response is to regulate the flow of en route aircraft by instituting miles-in-trail restrictions. MIT restrictions enforce greater than normal inter-aircraft spacing, prevent flights from passing each other en route, and, coupled with speed reductions, can greatly reduce the rate at which new aircraft arrive at an already-congested air space. Effectively, MIT restrictions create one or more extended FCFS queues, sometimes exceeding 1000 nautical miles in length (Green, 2000), upstream along the airways leading to an airport. By extending the physical size of the queue, MIT restrictions avoid the local density of a large stack and increase the safety of the NAS. A second, marginal benefit to slowing the speed of en route aircraft is a reduction in fuel costs in comparison to stacking.

In application, MIT restrictions are extremely flexible as they can begin in the airspace adjacent to the destination airport at any time and then radiate out along the airways as necessary. Through changes in required airspeed and spacing, the rate at which aircraft are fed into the stack-airport system can also be subtly adjusted. The predominant limit of miles-in-trail restrictions is that, despite their effectiveness in reducing congestion around an airport, the financial costs to users of the NAS remains high as aircraft continue to take delays in the air. Furthermore, during periods of heavy congestion, the length of mid-air queues can reach the airports of departure, in which case more drastic ATFM steps must be taken.

Due to their utility, MIT restrictions are a commonly used air traffic flow management technique. In 1998, for example, the FAA imposed MIT restrictions for an average of 5,000 hours, impacting 45,000 flights, per month. The usefulness of MIT restrictions depends on how early they can be implemented, as more aircraft can be delayed en route, rather than in the less-efficient stacks. Anticipation of congestion and delay is, therefore, important to the success of MIT restrictions; understanding when future congestion is likely, or whether existing congestion is likely to increase rather than dissipate, is key to successful air traffic flow management.

Section 2.1.2: Ground Delay Programs

The second strategic response to anticipated congestion is to initiate a ground delay program (GDP). In purpose, a GDP is intended to be similar to MIT restrictions and reduce the rate at which new flights enter the terminal airspace and the arrival queue. Instead of delaying flights en route, however, GDPs assign delays that must be taken on the ground before departure. Ground delays are, in theory, calculated such that the projected arrival times are the same as if each flight had departed on time and then experienced an airborne delay in queue before landing. The primary advantage of ground versus airborne delay is that delays on the ground are safer and require far less fuel. As ground delay is taken before aircraft depart, however, a GDP must be planned well in advance; this tradeoff of time vs. information is especially important to the effectiveness of a GDP.

> Tradeoff #1: the sooner an air traffic management response to anticipated delay is implemented, the greater the effect it will have on reducing potential delay costs, but the less information will be available about the true potential for congestion.

Though the impacts of GDPs on congestion are less immediate than MIT restrictions, the beneficial exchange of air for ground delay can significantly reduce the overall cost. Not only are safety concerns alleviated, but some flight costs associated with airborne delay (fuel, maintenance, cost of a possible diversion) can also be dramatically reduced or eliminated. For

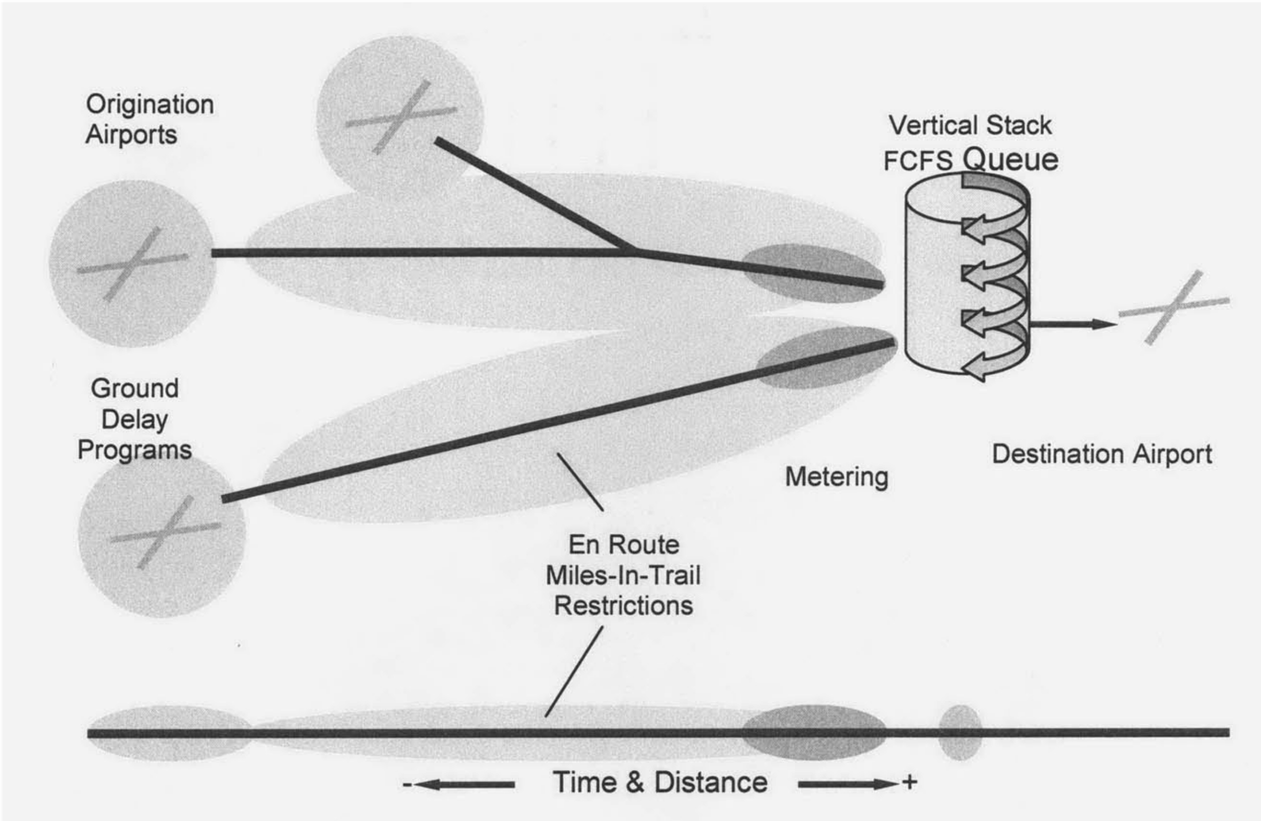

Figure 2-1: ATFM techniques used to manage arrival demand at an airport and their effective range

long delays, these cost savings can be particularly substantial. Furthermore, if notified of delays before departure, airline operators have the opportunity to adjust their flight schedules to minimize their impact on a flight network.

In practice, GDPs are designed by a traffic manager (TM), who determines for how long and to which flights ground delays are assigned. Although an ideal program will translate the anticipated airborne delay of each flight into an equal – and no greater – amount of ground delay, the first tradeoff implies that this perfect program can rarely be achieved; many hours in advance, perfect information on anticipated congestion is not available to the TM. The challenge in the design of a GDP is to minimize the overall delay costs using incomplete information on the future demand and capacity of an airport. As a result, a proposed program may be inappropriate for the level of congestion that actually materializes.

Tradeoff #2: If a GDP undercontrols and does not delay enough flights on the ground, it will be ineffective at preventing future airborne delays; if it overcontrols, flights will be delayed more than was necessary and runway capacity at the destination may go unused.

During the design process, a TM can customize different aspects of the GDP. For example, not only can the rates at which the GDP delivers aircraft to an airport be adjusted, but application of the program can also be restricted to certain origination airports based upon distance to the destination (please see §2.3.2) or other criteria. The choice of the airports to be included in a GDP determines how responsive a program will be to both the current and future forecasts of arrival capacity. In complement to the immediate response of MIT, GDPs offer a scalability for even the most severe delays in the NAS: a GDP can expand to become a ground stop, whereby all flights to an airport are held on the ground. Figure 2-2 summarizes the different ATFM responses to congestion.

Response Type	Metering	Miles-In-Trail	GDP
Scope	Tactical	Tactical	Strategic
Method	Regulate aircraft flow across a virtual boundary	Regulate aircraft flow along air routes Reduce airspeeds	Hold aircraft on the ground before departure
Benefits	Moderate safety benefits	Moderate safety Moderate fuel	Maximum safety Maximum fuel
Response Time	Immediate	Immediate	Substantial (Hours)
Risk	Increase fuel costs	Increase fuel costs and flight times	May delay flights more than necessary Wastes airport capacity
Controls	Metering Rate Number of boundaries	Airspeeds Required Spacing	PAARs Included Flights
Maximum scale	Very limited	Speed and spacing of all airborne flights	Ground stop of all flights

Figure 2-2: Three ATFM responses to arrival delays

The flexibility and scalability of a GDP belie a third tradeoff that exists for ground delay programs. In addition to the amount of information, the accuracy and precision of available information is also proportional to time (Figure 2-3). Although this relationship is very similar to Tradeoff #1, the subtle difference between the strict availability and quality of information elucidates a key difference in how ground delay programs are approached from a planning perspective than other, more reactive, ATFM techniques. In addition to time, the design of a ground delay program is dependent on the quantity and quality of information available to the traffic manager:

> Tradeoff #3: The sooner a GDP is implemented, the greater the ability it will have to prevent airborne delays, but the more likely that the available information will result in a program that over or undercontrols.

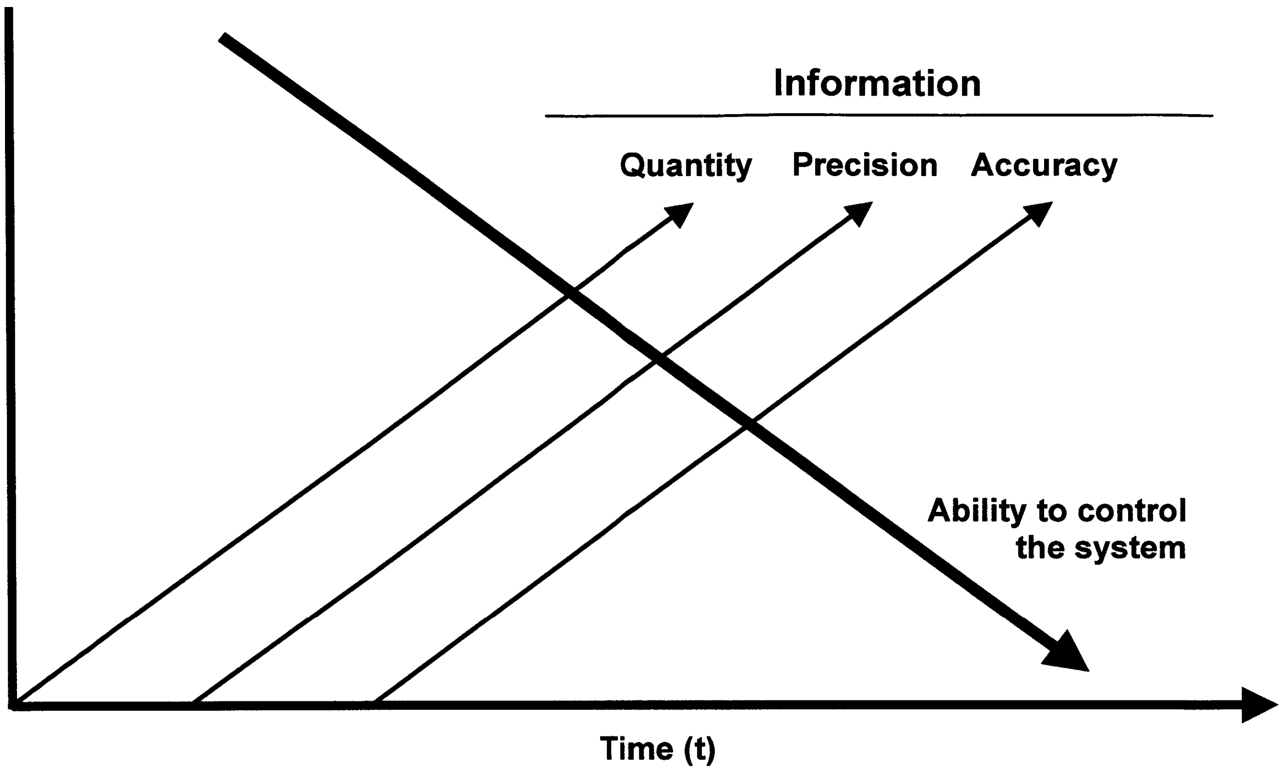

Figure 2-3: The relationship between time and information

To address the increased sensitivity of a ground delay program to time and information, a set of algorithms and tools have been designed to allow the traffic manager and other participants to adjust the effects of the program after it has been implemented, or filed. One approach, referred to as Collaborative Decision Making (CDM), allows participants[5], themselves, to reallocate delays. Furthermore, ground delay programs can be, and often are, implemented in tandem with miles-in-trail restrictions or other ATFM strategies, which allow for the fine-tuning of a coordinated ATC response to congestion.

To conclude this first section on ground delay programs, the first three tradeoffs can be summarized:

> Tradeoff Summary: A ground delay program trades the uncertainty of airborne delays in the future for the certainty of ground delays in the present.

Ground delay programs will be discussed in greater detail in §2.3.

Section 2.2: Forecasting Flight Delays in the NAS

The tradeoffs between time, information, and effectiveness (§2.1.1 and §2.1.2) are especially important for the implementation of a GDP, which has a longer response time but offers greater cost-reduction power than other ATFM techniques. To maximize the benefits

[5] U.S. domestic airlines and alliances

while minimizing the risk of overcontrolling, traffic managers must anticipate when, at what airports, and to what extent the demand for arrivals will exceed capacity. Although, at any moment, accurate information about the current state of the NAS is always available, as TMs look minutes and hours ahead in time, two factors increasingly reduce the accuracy and precision of forecasts and complicate the planning of ground delay programs: uncertainty and a lack of information on future events in the NAS.

Section 2.2.1: Uncertainty in the NAS

Uncertainty in the NAS reduces the accuracy and precision of congestion and airborne delay forecasts that are key to managing the tradeoffs of a GDP. The cumulative number of unexpected events increases with time, as do their impacts on the NAS. For example, weather patterns change, flights are cancelled, or new, unscheduled flights added – all of which have ramifications on airborne delays. Correspondingly, the accuracy and precision of forecasted arrival demands and capacities decrease as TMs look farther into the future, reducing the efficacy of ground delay programs.

In general, there are six types of uncertainty relevant to strategic ATFM decisions:

Aggregate aircraft arrival demand: Uncertainty in aggregate arrival demand is due to three primary sources: flight cancellations, additions, and drift (Ball and Hoffman, 2001). Cancellations, for example, can occur due to maintenance issues, weather, or other airline schedule changes, and predominantly affect commercial flights. Drift is the deviation of a flight from a forecasted arrival time, often due to changes in airspeed, atmospheric winds, and routes.

Aggregate aircraft arrival capacity: Actual airport arrival rates (AARs) are a function of the order and type of flight arrivals and ambient weather conditions in the terminal airspace that determine how the available runways can be used safely for aircraft arrivals, which is also referred to as the choice of runway configuration. Weather conditions can be highly variable and have the potential to dramatically reduce the arrival capacity of an airport within a short period of time.

ATC Actions: Forecasts of arrival demand are impacted by strategic traffic management initiatives (TMIs) and the tactical actions taken by flight controllers. For example, the rerouting of flights around a storm by air traffic controllers will delay the expected arrival times of rerouted flights; a change that is not known until the reroute is proposed.

Aircraft response: To a lesser extent, the response of aircraft to proposed ATC actions is also a source of uncertainty in the system. Given route changes or excessive delays, aircraft may request further route/airspeed changes or divert to another airport, all of which will cause the time/location of arrival demand to change from the forecast.

Airline response: Airlines also react strategically to changes in the NAS. Scheduled flights[6] can be cancelled in response to lengthy, anticipated delays – cancellations that further impact arrival demand forecasts.

[6] TMIs can also impact popups, which may become more or less likely as delays are anticipated.

Delay Costs: Different types of delay have different fixed and variable costs; for example, ground delay saves on fuel costs over airborne delay. For GDPs, which try to exchange one type of delay for another, the comparative differences between different cost structures determine the appropriate mix of delay. These structures, however, are often unclear, especially when exogenous network effects – such as the propagation of delays throughout a commercial carrier's daily operations – are included.

For planning ground delay programs, the sources of delay in the NAS can be generally categorized according to a number of different qualities, for example, by demand or capacity, as an action that causes delay or a reaction to anticipated delays, or by the scope of the source (Figure 2-3). Although all sources are important, the incorporation of the uncertainty of each source into the planning of a GDP depends on the information available to the traffic manager. One source, weather, is particularly relevant to this discussion as it is not only the primary source of uncertainty for airport capacity (as illustrated by Figure 2-4), but is also within the domain of knowledge of the air traffic controller.

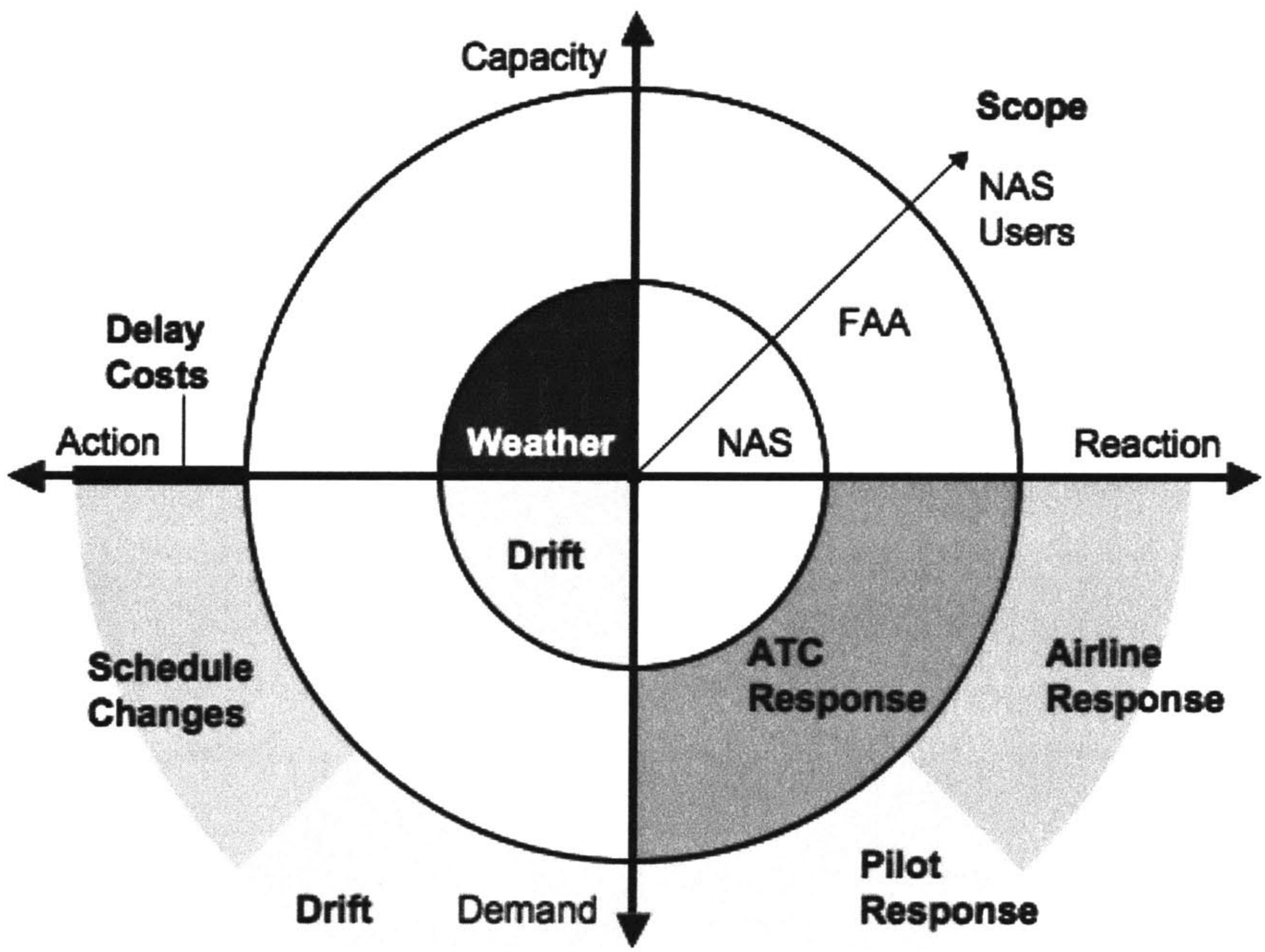

Figure 2-4: Categorization of types of delay in the NAS

Section 2.2.2: The Enhanced Traffic Management System

To provide information about the NAS for improved ATFM decision-making, the FAA maintains a real-time model of air traffic in the NAS. For ground delay programs, this model, the Enhanced Traffic Management System (ETMS), is used to forecast the demand for arrivals over time at airports in the US and identify potential airborne delays before they occur. A key output of ETMS is the time that each flight is expected to request to land or otherwise do so if not shunted into a stack, holding pattern, or other airborne queue. ETMS empirically estimates this time, herein referred to as the demand time, using current, available, flight data, such as location, proposed route, airspeed, and destination. In aggregate, the total number of aircraft that are projected to enter the terminal airspace of the destination airport and request to land[7] per unit time is known as the expected demand rate; demand, arrival, and capacity rates are often reported in 15-minute intervals.

The following times are pertinent to ETMS arrival demand forecasting:

- File Time (or Flight Plan)[8]: The time at which a flight plan is filed for a flight
- Gate Departure Time (GTD): The time an aircraft departs from the gate
- Wheels-Up Departure Time: The time an aircraft becomes airborne
- Demand Time: The time an aircraft is ready to begin the final landing approach or enter an airborne queue. This time is also referred to as the time an aircraft "enters the terminal airspace" of the destination airport.
- Runway Arrival Time (RTA): The time an aircraft lands at the destination airport
- Gate Arrival Time (GTA): The time an aircraft reaches the gate at the destination airport

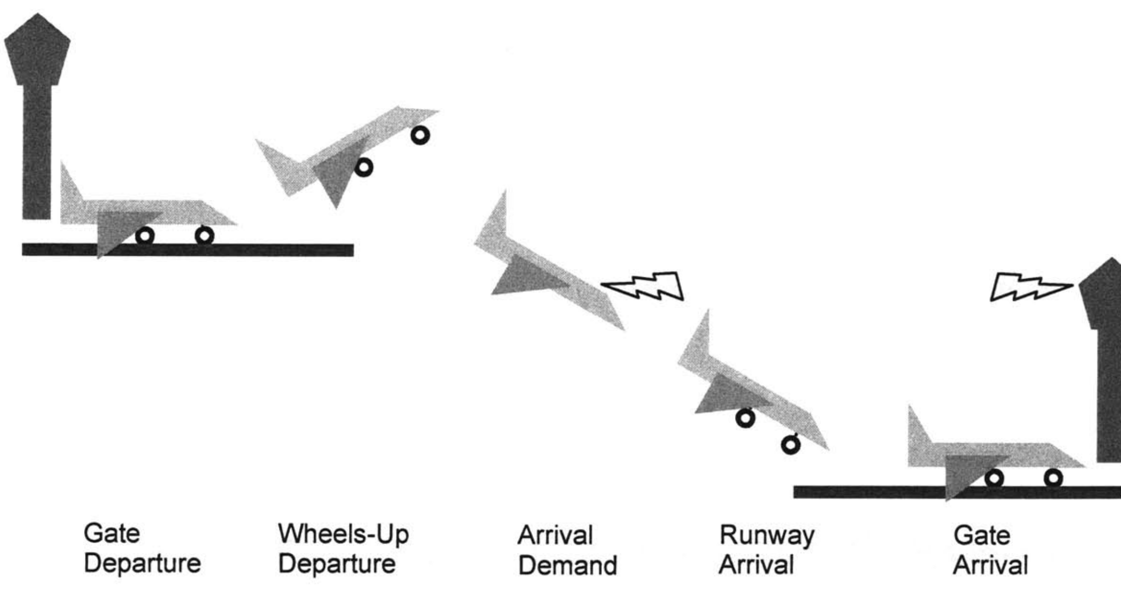

Figure 2-5: Flight times relevant to ETMS arrival demand forecasts

[7] ETMS can also be used to forecast times for the landing and gate arrival of aircraft, for example estimated runway time of arrival (ERTA). These times are based on the outputs of a GDP.
[8] File time can also refer to the time at which a GDP is created; see §2.3.1

In general, for the purposes of strategic air traffic flow management[9], data types can be generally divided into three broad categories based on the status of flights they encompass: flights currently en route, flights that have filed a flight plan, but have yet to depart, and flights that are scheduled to take place but have not yet filed a flight plan (see Figure 2-6). Over time, as flight plans are filed and flights depart, ETMS updates flight projections with the most recent information. Actual flights can differ substantially in time and route from flight plans and schedules, so ETMS projections of airport arrival demand times are most accurate for flights that have departed and least for those flights for which a flight plan has yet to be filed. For projections farther ahead in time, fewer flights will have departed or filed flight plans, and less information will be available for projecting demand for arrivals.

Types of ETMS Data

Flight schedules are the first form of information that the FAA may receive about a flight. For the major commercial air carriers, schedules are published weeks or months in advance and included in the Official Airline Guide (OAG), a seasonally updated database of scheduled flights. The OAG is not maintained by the FAA and is primarily intended to support the sale of tickets for commercial services – it will not include any general aviation (GA), charter, air taxi, military, or, for the major carriers, non-revenue or otherwise unscheduled flights. The OAG database is referenced on a weekly basis by ETMS for flight origins and destinations and the scheduled gate departure times. Although scheduled gate arrival times are also included in the OAG, they are not precise enough for strategic ATFM purposes. ETMS, therefore, projects the demand time from the runway departure time, flight path, and cruising air speed, which are, in turn, projected based on the scheduled departure time and flight characteristics (carrier, origin, destination, and aircraft type) provided by the schedule.

The utility of OAG data for ground delay programs is rather limited. Not only is the OAG lacking many flights[10], but the data, itself, is likely to be replaced by much more accurate data long before a ground delay program would be planned. Only in those cases when a commercial air carrier has yet to provide more detailed flight information – a flight plan – is the OAG used: when the GDP is planned many hours in advance or has an extended duration.

Flight plans are the second type of data used by ETMS and are a significant improvement over OAG data. A typical flight plan is filed, or submitted to the FAA, by the pilot or aircraft operator in the hours preceding departure and contains the origin, destination, proposed route, and expected gate departure time of a flight. Although airspeed is not included, ETMS can use the standard cruising speed for the aircraft type and so be able to project the time at which a flight will reach its destination. Unfortunately, the quality of flight plan information – the accuracy and level of detail – is not standard across the industry, nor is the timing with which a plan is filed. Not only can the route information be incomplete or lacking detail, but also flight plans, themselves, may not be filed until a flight is airborne[11].

The most accurate information is for flights that are en route. Using a variety of data sources, including radar returns and communication with the aircraft, ETMS gathers and records the most recent location, altitude, and airspeed of each flight. From this current data, previously

[9] For a more detailed discussion of the myriad sources of flight data, please see the "Enhanced Traffic Management System (ETMS) Functional Description," Version 7.8

[10] For those airports that are likely to be considered for a GDP, however, a substantial percentage of flights are generally available in OAG data.

[11] For example, if a pilot decides to fly IFR or increase altitude above MSL 18,000 ft (FAA)

entered route information, and current wind speeds along the proposed route, ETMS then projects the future location of an aircraft over time and the time when it will reach its destination airport. As ETMS receives updated positioning information on each flight, the actual position of an aircraft is compared to the expected path; when there is a discrepancy, ETMS revises the forecasted route and demand time. The frequent updates and comprehensiveness of en route data makes this the most reliable source for estimating the arrival demand at an airport; the primary limitation to data for en route flights is that, once airborne, a flight cannot be included in a ground delay program. En route data, therefore, is only useful for GDP purposes when additional flights are still on the ground.

Flight Status	En Route	Flight Plan Filed, flight departed	Scheduled (No Plan), flight not departed
Data Source	Many (e.g. TRACON)	Flight Plan	OAG
Time Available	Wheels-Up Departure Time	After or Hours Before Departure	Weeks Before Departure
Information	Aircraft Type Airspeed Destination Location Route	Aircraft Type Destination Location (origin) Route (partial)	Aircraft Type Destination Location (origin)
ETMS-Projected Flight Data	Arrival Demand Time	Arrival Demand Time Airspeed	Arrival Demand Time Airspeed Route
Flights without ETMS Data	Non-Departed	Non-Commercial flights that have not filed	General Aviation Military Unscheduled Commercial

Figure 2-6: Types of data used by ETMS to forecast arrival demand for an airport

The Sensitivity of Ground Delay Programs to Forecasted Demand

There are two main types of uncertainty present in ETMS demand forecasts: drift, and overall demand. First, as previously defined, drift refers to the small changes in anticipated arrival time that occur once a flight is already en route and result from changes in wind speed, airspeed, route, etc. that are an inevitable part of flying. As drift is, in part, a function of time and distance, the farther a flight is from the destination airport, the greater the effect that drift can have on the flight's arrival time. However, the overall effects of airborne drift tend to be small as localized wind speed changes over a route are often independent of each other and balance out. Furthermore, at the discretion of the pilot, aircraft increase or decrease airspeed in response to larger wind speed changes, mitigating wind speed changes. In their study on the effects of uncertainty in arrival demand on ground delay program performance, Ball and Hoffman (2001) approximate drift by a uniform distribution (U[-5, 15]), whose effects on individual aircraft demand times, although not insignificant, are alleviated for GDP purposes by the aggregation of demand across flights into 15-minute intervals.

In a more general sense, for flights that are still on the ground, the concept of drift can be extended to include groundside changes. As part of ETMS, ground taxi times are independently modeled (by empirical observations) for both origin and departure airports; when applicable, ETMS adds these times to the gate departure time. Larger ground delays, for example, those due to mechanical problems, can have an impact as flights generally arrive later and not earlier than planned. We are not aware of any research on the general effects of maintenance and other substantial delays on ETMS demand forecasts, but the effects can be expected to be small, on the order of 1-2 additional/reduced arrivals per hour.

The second type of demand uncertainty relates to flight cancellations, or, more importantly, additions. Although a cancelled flight reduces demand and may result, at most, in an unused arrival slot, additional flights can cause complications. Recall that a GDP is implemented when the number of arrivals at an airport already exceeds capacity. In principle, all of the future arrival slots have already been assigned[12], so that arrival demand by a single, additional flight – which may not be subject to GDP delays – may cause up to several hours of airborne delay for itself or for the system, as a whole. In ATFM terminology, any flight that files a flight plan (without OAG schedule data) after the start of a GDP is referred to as a "popup". The occurrence of popups is generally limited at most commercial airports (1-2 per hour).

Section 2.2.3: Arrival Capacity Forecasts

The forecasting of airport arrival capacity is not as formalized as that of demand. The actual number of arrivals at an airport is a function of the approach speed and spacing of inbound aircraft as they pass the outer marker and enter the final approach. Controllers base spacing on two principal factors, the aircraft arrival order and the runway configuration in use.

First, for safety reasons, the spacing between aircraft at the outer marker is set such that the actual spacing along the entire final approach path never drops below a minimum threshold. Approach speed and the generation and reaction to wake turbulence vary by aircraft type, so the required spacing between aircraft is not uniform. Furthermore, speed and spacing can become even more complicated when multiple adjacent runways are used for landings or when one runway is used for both takeoffs and landings. For strategic ATFM planning purposes, however, the fluctuations in arrival capacity caused by aircraft demand order are small enough to be approximated by a historical average capacity. In practice, the arrival rate at any given airport is assumed to be a known constant for any given combination of runway configuration and weather conditions.

The second factor, runway configuration, is a function of the ambient weather conditions (wind speed, direction, and variability, visibility, and precipitation) and is much more important for the planning of a ground delay program. The ambient weather at an airport can change both the runway configuration and the safety requirements for speed and spacing among aircraft on the final approach path. While aircraft arrival order has a relatively small effect, inclement weather can routinely drop the arrival capacity of an airport by as much as 50% almost instantaneously as a change in configuration may reduce the number of runways used for arrivals from two to one. Furthermore, the timing and severity of a weather event may not be known

[12] In practice, TMs often design ground delay programs with a capacity buffer to informally account for potential additional demand

with little more than just a few minutes warning. To anticipate arrival capacity rates, traffic managers rely on experience, knowledge of possible runway configurations, and static, deterministic weather forecasts, as well as real-time weather information, such as Doppler radar returns. In §2.4, new weather forecasting technology and its implications on the information presented to traffic managers will be discussed.

Section 2.3: Designing Ground Delay Programs

In designing a ground delay program, a traffic manager must balance many factors to reduce the overall cost of delays to the system. A software tool called Flight Schedule Monitor (FSM) is currently employed by traffic managers to model and evaluate a proposed GDP with respect to these tradeoffs. FSM requires ETMS forecasts of flight demand and the expected arrival capacity profile of an airport, which is provided by the traffic manager, and outputs the assignment and accumulation of ground delay and the projected arrival times of flights.

Section 2.3.1: GDP Mechanics

When current information about future arrival demand and capacity at an airport suggests that flights are likely to experience airborne delay, a TM can respond by using FSM to create a ground delay program. The primary input to a GDP is a set of *Planned Airport Arrival Rates* (PAARs), which are used by FSM as the desired rate at which flights should be rescheduled to arrive at the airport. PAARs are often set as capacities for 15-minute increments and, together in succession, form a *capacity profile*. For example, under perfect weather, a TM might expect an airport to accommodate up to 100 arrivals/hour, and when it is raining, only 60. For 15-minute time periods, these PAARs would be 25 and 15 arrivals/period, respectively. Figure 2-7 illustrates two possible capacity profiles using these capacities, one (FC 1) for perfect weather and a second (FC 2) for a brief rain storm between 15:30 Z and 16:00 Z.

When setting PAARs, however, the TM does not need to use a rate that the airport would actually achieve. In the previous example, the TM could set the PAARs to be 20 arrivals/period, a rate that indicates either an expectation that the capacity of the airport will change during the time period, or that the actual arrival rate, or AAR, at this future time is uncertain – simply put, it may or may not rain. Even though the deterministic information provided to the traffic manager does not capture the range of possible outcomes, this informal hedging on arrival rates reflects an inherent understanding that multiple outcomes are possible. The traffic manager, by adjusting PAARs, attempts to balance the perceived costs of either too weak or too strong a GDP, previously discussed as the second tradeoff.

Although a full discussion of TM strategies for setting PAARs is outside the scope of this thesis, some terminology will aid in describing the process by which a GDP is implemented. The time of the first PAAR is referred to as the start time; in contrast, the time at which a GDP is implemented is called the GDP file time. For a new program, the GDP file time will usually precede the start time by one or more hours (see Figure 2-8).

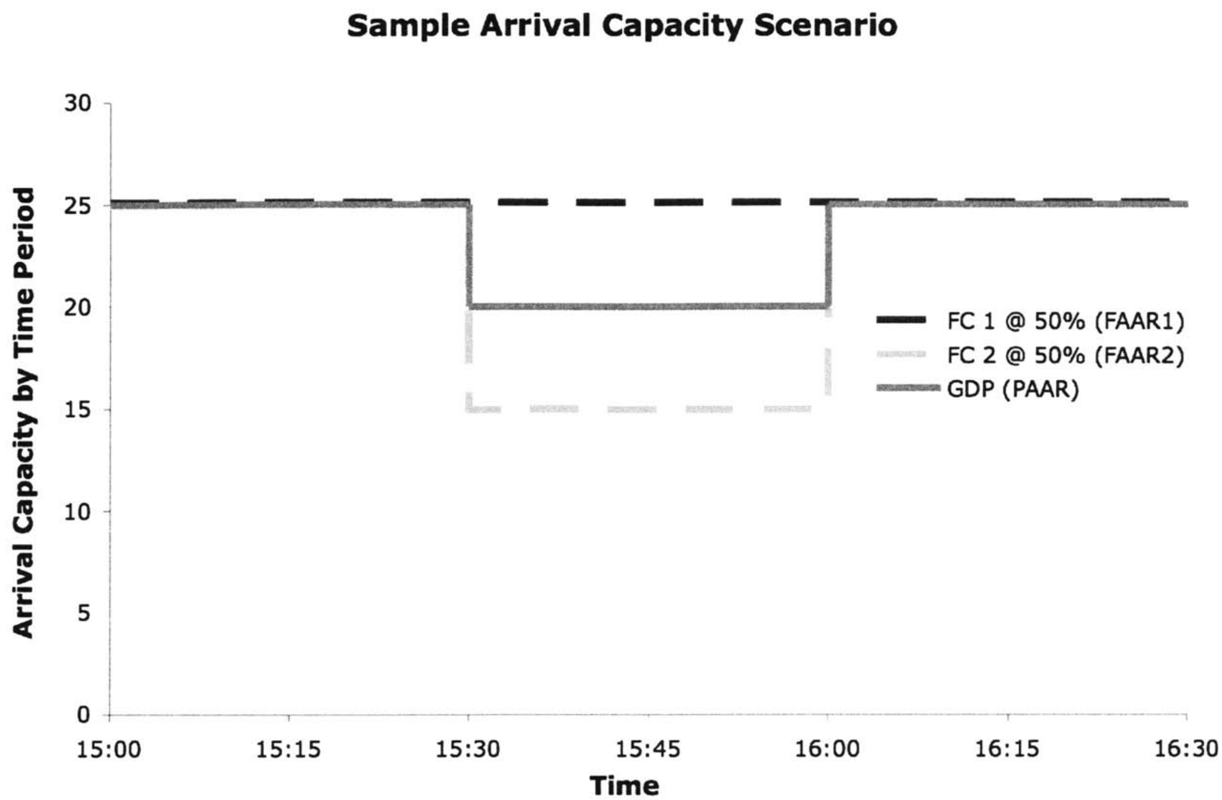

Figure 2-7: An example of the possible outcomes considered by a Traffic Manager

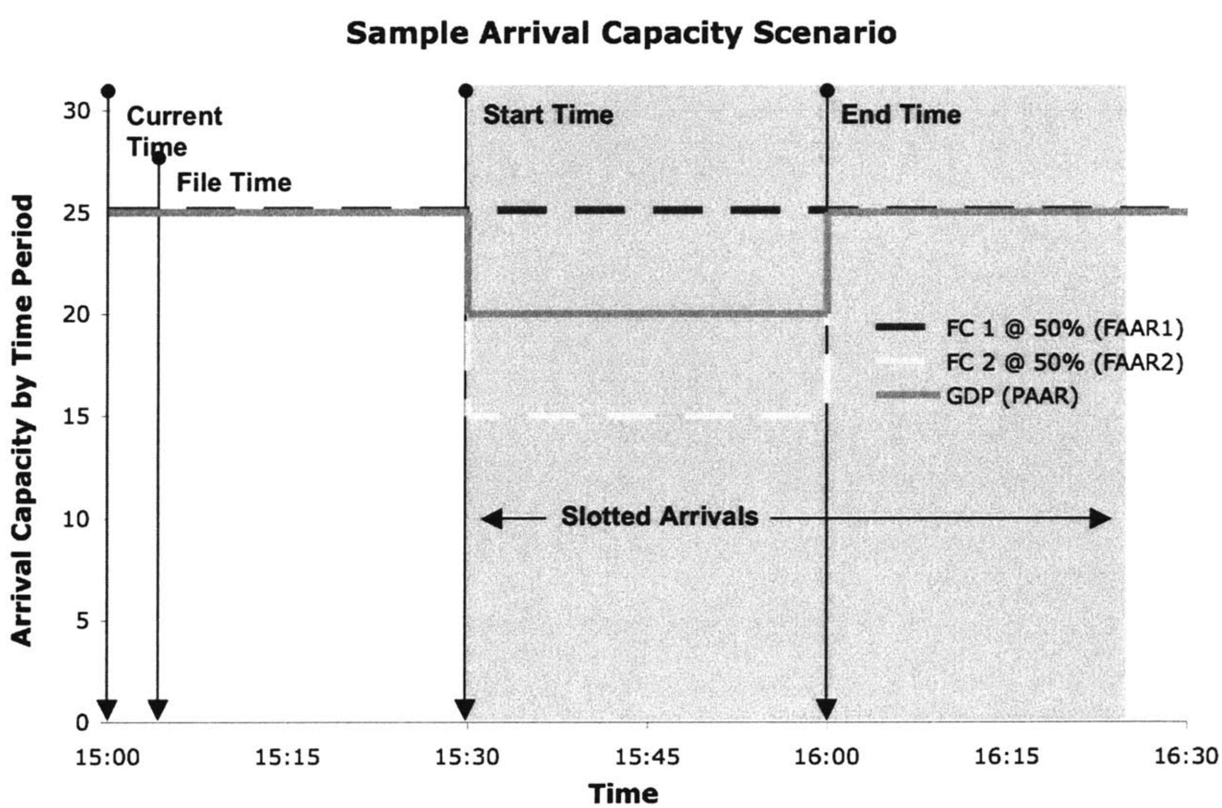

Figure 2-8: Timeline of a ground delay program

The following terms are useful to describe a ground delay program:

- Actual Arrival Rate (AAR): the actual, after-the-fact, arrival capacity of an airport; expressed as a rate of arrivals during a period of time, often an interval of 15 minutes
- Planned Airport Arrival Rate (PAAR): the future airport arrival capacity rate proposed by a traffic manager for a GDP for an interval of 15 minutes
- Base Capacity: The number of arrivals that could occur at an airport under ideal atmospheric conditions
- File Time (GDP): The time at which a proposed GDP is implemented, or becomes active
- Start Time: The time of the first period in which a TM sets PAARs less than the maximum capacity of an airport; time of the first slot created by a GDP
- Exempt Flight[13]: A flight that is not subject to a ground delay program even though the flight is expected to arrive after the start time; for example, a flight that is already airborne is exempt
- Slot: a unit of time in which there will be an opportunity for a single aircraft to land

Provided with a set of PAARs, or a capacity profile, an algorithm is used to divide each time period by the number of planned arrivals, each of which corresponds to an arrival slot. The t^{th} slot of period i has unit capacity and can be defined by its start and end times as:

$$\text{Slot}_{t,i} : [\text{start}_{t,i}, \text{end}_{t,i})$$

$$\text{start}_{t,i} = \text{start}_i + (t-1) \times \frac{\text{dur}_i}{\text{PAAR}_i} \qquad (f2.1)$$

$$\text{end}_{t,i} = \text{start}_i + t \times \frac{\text{dur}_i}{\text{PAAR}_i} \qquad (f2.2)$$

where

$\text{Slot}_{t,i}$ is the t^{th} slot in time period i
$\text{start}_{t,i}$ is the start time of the t^{th} slot in period i
$\text{end}_{t,i}$ is the start time of the t^{th} slot in period i
start_i, is the start time of period i
dur_i is the duration of time period i, assumed to be typically equal to 15 minutes
PAAR_i is the number of planned arrivals during time period i

The assignment of flights to arrival slots is performed in two stages. First, flights that are exempt from the program are assigned to the first available slot at or after their scheduled arrival times. Exempt flights include international or airborne flights or those otherwise not included by the TM in the GDP. Next, included flights are assigned by an algorithm called Ration-By-Schedule (RBS) to the remaining slots in order of arrival time[14]; if scheduled arrival time is used, the algorithm used is called RBS++. Working backwards from the time of the arrival slot, ground delays are assigned to included flights.

[13] Within the scope of this thesis, "Exempt" and "Excluded" flights are identical
[14] Other times, such as estimated arrival time (ETA) can be used

Section 2.3.2: Traffic Manager Inputs to a GDP

To adjust both the severity and manner in which delays are assigned to flights, traffic managers control a series of inputs to FSM. Much like the overall design of a GDP, each input also represents a tradeoff that must be carefully weighed in the design of a program.

Planned Airport Arrival Rates

For FSM, the traffic manager provides a capacity profile consisting of planned airport arrival rates over the time horizon of a GDP. The PAARs determine the number of arrival slots, which, in turn, determine how much delay must be assigned to flights to accommodate the given arrival rate profile.

Tradeoff #4: Increasing a PAAR increases the amount of ground delay assigned by a program, decreasing the rate reduces assigned ground delay.

A capacity profile may consist of a sequence of many PAARs, each of which represents the capacity for a single 15-minute interval. The traffic manager can adjust the PAAR for each interval independently and, as a result, create a program that is more restrictive during some periods of time and less so during others. Furthermore, the impact that adjusting a particular PAAR will have depends on the other PAARs and level of demand over the entire program. The optimal assignment of PAARs is very complex, especially under uncertainty, and is beyond the scope of this thesis. For additional information, the reader is encouraged to refer to the literature. Both Richetta and Odoni (1994)[15] and Mukherjee (2005)[16] present optimization models that assign flight ground delays given a dynamic, stochastic arrival capacity forecast.

In FSM, the PAARs serve a dual function. First, as part of the algorithms used to create a program, the PAARs are the arrival rates that FSM tries to match when revising the scheduled flight arrival times. Second, the PAARs are assumed to be the AARs – the *actual* arrival acceptance rates – for the purposes of estimating the airborne delay that will occur given a proposed program. By assuming that the planned and actual rates are equivalent, airborne delay is essentially set to zero because aircraft are scheduled by the GDP to arrive at the demand time. FSM takes this assumption one step further and does not even calculate airborne delay. As will be discussed in §2.5 and §3.2, our research will focus on this second usage: the development of an analysis tool to study what happens when the PAARs are not realized.

Start Time

The start time of a program is the time of the first arrival slot and, for practical purposes, is also the time at which the PAARs are reduced below the normal operating capacity, or base. From an analytical standpoint, regardless of the PAARs, the start time can be considered as the time before which no flights that are scheduled to arrive will be included in the ground delay program, regardless of overall demand and capacity. Thus, the effect of adjusting the start time is to change the flights that may be included in a program; an earlier start time will include more flights and a later time, fewer.

Tradeoff #5: Moving up the start time of a program allows additional flights to be included based on their scheduled arrival times, delaying exempts flights.

[15] "Dynamic Solution to the Ground Holding Problem in Air Traffic Control", *Transportation Research* 28a
[16] "Dynamic Stochastic Optimization Models for Air Traffic Flow Management", University of California, Berkeley

Including a flight in a program provides FSM with the option of assigning ground delay to that flight, but does not guarantee that ground delay will be assigned. As a simple example, consider a proposed program whereby two flights, A and B, are both scheduled to arrive at 12:59. With a start time of 13:00, both flights will be excluded from the program and will receive no ground delay but with a 12:45 start both flights could potentially be given ground delay. Furthermore, suppose that there are two arrival slots for flights A and B, one at 12:59 and the second at 13:00; in this example, one flight, A, will receive one minute of ground delay so as to arrive at 13:00.

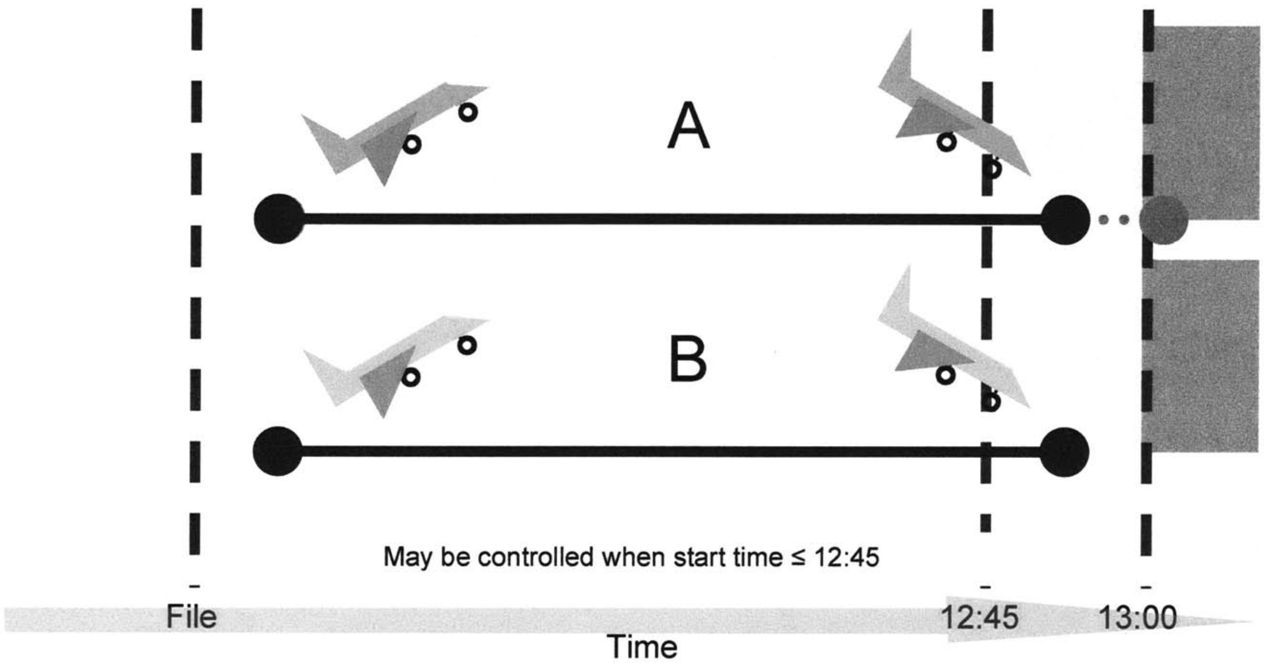

Figure 2-9: Time-Location chart for flights A and B: Start Time Changes

File Time

The file time of a GDP is the time at which a program is implemented and all included flights are informed of their assigned ground delay. While the start time of a program determines which flights are included based on scheduled arrival time, the file time of a program discriminates based on the *departure* time: any flight that departs before the file time can not be controlled regardless of when it is scheduled to arrive.

Tradeoff #6: Moving up the file time of a program allows additional flights to be included based on their scheduled departure times, delaying exempts flights.

The otherwise simple relationship between start time and the number of included flights is complicated by flight departure times and the program file time – changes to the start time affect short- and long-haul flights differently due to the scheduled departure times of these flights. Consider the previous example with flights A and B, now assuming that flight A departs at 10:30, and B at 11:30, one hour later. When the file time of the program is 10:00, the adjustment of start time is as before, either or both of flights A and B can be controlled, or neither flight is. If the file time of the program is postponed to 11:00, however, flight A cannot be controlled and B will receive any assigned delay.

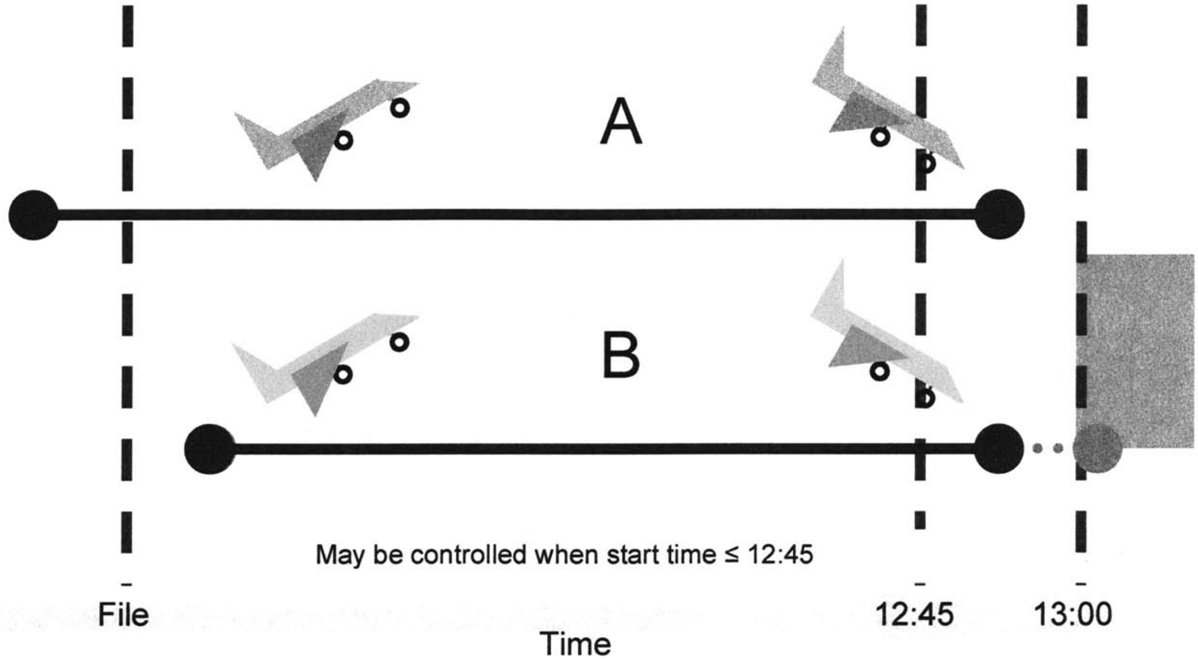

Figure 2-10: Time-Location chart for flights A and B: File Time Changes

Included Airports

A traffic manager can also exempt flights by airport of origination.

Tradeoff #7: Exempting all or some of the flights originating at a specified airport(s) reduces the number of flights that can be controlled.

Although FSM allows the exclusion of individual airports, it is common for traffic managers to exempt domestic airports[17] by tiers, or regional groupings. In practice, these exclusions are based on the distance from the airport for which a GDP is being proposed, with flights from more distant airport groups being those most likely to be excluded.

In conjunction with the file and start time tradeoffs, the exclusion of flights by distance poses a question of equity to the

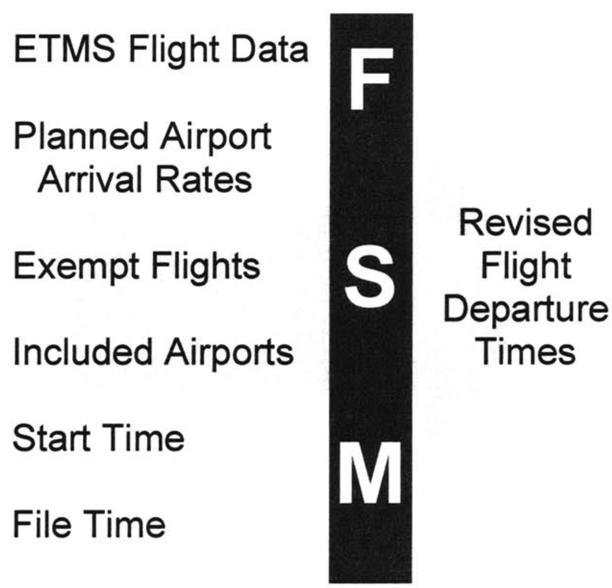

Figure 2-11: GDP inputs and output

[17] All international flights are exempt from a program

traffic manager. By exempting long-haul flights, a traffic manager is hedging against the likelihood that the capacity at an airport will be greater than expected and that, over time, updated weather forecasts will show that holding long distance flights would have resulted in unnecessary delays. If the reduction in capacity is realized, however, the burden of delay will then be placed upon those flights that are still on the ground, which are also those flights with shorter en route times. Equity will be discussed further in §2.3.4.

> Tradeoff #8: Using origination-based or time-based inputs to a ground delay program to exempt long distance flights allows a traffic manager to delay the effects of a program until a later time when more information may be available, but places the burden of delays on a reduced set of shorter flights.

Figure 2-11 summarizes the key inputs to a GDP.

Section 2.3.3: GDP Design Objectives

When considering the implementation of a ground delay program, a traffic manager ultimately asks two questions:

1. Is it preferable to implement a program now or to wait for more information?
2. If a program is implemented now, what is the preferable design?

Recall from the discussion on the tradeoffs faced by the TM that these two questions are inherently related; a program cannot be designed without considering when and how new information will become available, which precludes consideration of whether it is better or not to wait. Faced with these questions, the preferable – fair, safe, and efficient – decision will balance the expected cost and equity of a GDP with how well the proposed program can react to changes of the capacity forecasts.

Cost, the first factor, depends on a multitude of different variables. As discussed in §1.2.2, the expected cost of a proposed program should account for both direct and indirect costs. Certain costs, like fuel, can be directly attributed to a specific aircraft and instance of delay, as aircraft in airborne holding patterns expend fuel at a given rate. Other costs, for example safety and disruption, indirectly depend on variables external to the flight, such as the location and number of other flights, schedules, and the operational policies of airlines. Furthermore, the cost of delay per unit time can also vary by the total amount of delay. For example, flight diversions have significant cost, but only occur after a significant period of airborne delay.

Unfortunately, the TM lacks the information required to even approximate these delay costs. Many of the direct and indirect costs (labor, network disruption) are internal to the airlines and are not formally available to the FAA. Furthermore, FSM does not incorporate any arrival capacity information other than the PAARs and, as such, only provides information on the expected ground delays of a GDP. Evaluating the tradeoff between air and ground delay costs is an extremely difficult proposition for the TM!

The second factor is the equity, or fairness of a program to affected flights. It can certainly be said that a program that ascribes all delay to a single flight is less desirable than one that distributes delay equally. Unfortunately, a more formal definition is difficult to achieve, as delays will never be spread evenly across all flights. In fact, variations in scheduled demand, flight origination, and the timing of inclement weather, may make a uniform distribution inequitable: should a flight that is scheduled to arrive during a period of low demand be delayed as much as one during a busy period? The difficulty in assessing GDP equity is complicated by FSM, which does not provide summaries of delay by aircraft. Thus, a good first-step to evaluating the equity of a program would be to begin looking at such a distribution.

The third factor, evolution, refers to the ability of a current GDP to be modified in the future in response to new information about the system. Over time, the anticipated arrival demand and capacity of an airport will change, or evolve, as weather forecasts are revised and flight information updated. Some GDPs can be more easily modified in response to these changes than others. For example, if weather forecasts are expected to improve, a traffic manager may favor a GDP that has many local flights that could be released from ground hold early. As forecasts can evolve in different ways, a traffic manager seeks to hedge against different outcomes through the tradeoffs discussed in §2.3.2 – often, making a GDP more robust to handle changes will increase the expected cost or distribute delays less equitably throughout the system.

The key tradeoff between flexibility and expected cost and equity is complicated by a lack of information. For the purposes of strategic ATFM decision-making, current decision-support software platforms do not provide the traffic manager with sufficient information to make informed decisions in certain cases. Key performance indicators, such as cost and equity, are not provided by FSM[18] and there no formal appraisal of how a proposed GDP might be adapted to changes in demand and capacity forecasts. Traffic managers must base their decisions on their own experience of how a given GDP is likely to perform. This thesis suggests how GDP decision support tools can be improved to include uncertainty in the information presented to the traffic manager. The next section explains the assumptions made by the model regarding probabilistic airport arrival capacity forecasts and how they can be applied to GDPs.

Section 2.4: Probabilistic Arrival Capacities

As detailed in §2.2, ground delay programs are subject to a range of uncertainties, of which arrival demand and capacity uncertainty have the greatest impact on the performance of a program. One unstated conclusion of that section, however, is that the demand forecasts used by FSM are significantly more accurate and precise than capacity forecasts. Not only is demand forecasting technology more advanced, but the structure of the information provided to FSM (individual flight tracking, real-time updates) facilitates the design of a GDP by the traffic manager. Although air traffic controllers do make extensive use of current weather data for tactical routing decisions, existing weather forecast technology is of only limited applicability to the more strategic design of a GDP. The projection of actual arrival capacity requires precise weather forecasts – both specific to the terminal airspace of an airport and to a window of time that can be measured in minutes, not hours. Recent developments in meteorological forecasting technology suggest that new, more precise forecasts may be possible.

For the analyses presented in this thesis, we first assume that discrete, probabilistic arrival capacity forecasts will be available. A single probabilistic forecast, also called a scenario, contains a finite number of individual capacity profiles, which represent possible values for the AARs over time. In Figure 2-7, a sample probabilistic forecast is shown. In this scenario, there

[18] FSM does provide some metrics, including "unrecoverable delay", which is defined as the amount of ground delay that will occur between the file time and the start time of the proposed GDP.

are only two possible outcomes: one represents the possibility that a storm will occur (with probability p) that reduces the arrival capacity of the airport; in the other, the storm does not occur (1 - p) and the airport remains at full capacity. We assume that, as part of a forecast, both the arrival acceptance rates and likelihood are known for each profile.

A second assumption made in our analyses is that probabilistic forecasts will be updated; if the forecast shown in Figure 2-7 is made at time T_0, then at some later time $T > T_0$, a new forecast will become available. One form of a possible update is a complete revision of the meteorological forecast, including new profiles and probabilities. Another, more simple example, would be that, at some point at or before the start of the ground delay program, we are able to determine with certainty which of the profiles will occur: either it does or does not rain. Updated profiles not only reflect a dynamic aspect of planning a ground delay program, but also they more accurately reflect the reality of weather forecasts.

Although both assumptions regarding the structure and updates of probabilistic forecasts do not currently apply, they are consistent with on forecast technology that is being developed. For example, at San Francisco International Airport (SFO), advanced meteorological forecasts are used to predict the time at which the morning fog will have burned off sufficiently to permit arrivals on two, parallel runways, as opposed to a single runway. These forecasts are both specific to conditions at the airport, and offer high time precision. In conjunction with research done at the MIT Lincoln Laboratories[19], probabilistic forecasts of exactly the type described have been developed for the fog pattern at SFO and are currently being incorporated into the GDP design process at the airport. The tool we have developed can be applied to any airport with probabilistic capacity and the example of SFO illustrates the reasonableness of our assumptions.

Section 2.5: The Utility of a Tool

Concerning ground delay programs, the decision-making of the traffic manager can be reduced to two simple questions, which were introduced in §2.3.3. Form the point of view for developing a tool to assist with decision-making, these questions can be restated as:

1. What action, if any, should be taken at the current time?
2. By what time can action be taken in the future to avoid airborne / ground delays?

Under current GDP decision-making practices, when faced with the possibility of lengthy airborne delays, a traffic manager answers these questions with a combination of experience and feedback from FSM about a proposed program. Although the ETMS data used by FSM provides valuable information about arrival demand, arrival capacities are based on the original PAARs, rates which are provided by the traffic manager and reflect the hedging of different possible outcomes. However, the analytical approach taken by FSM, and the results it derives, assumes that these rates are as informed as ETMS data.

In this thesis, we propose to create a new analytical tool that incorporates the probabilistic and dynamic nature of arrival capacity forecasts into the planning of a ground delay program. In Chapter Three, the results of the tool will be discussed, illustrating the adaptation of existing metrics and proposals of new metrics for the probabilistic environment. Using these new analyses, a traffic manager may be able to make more informed decisions regarding the

[19] "SFO Marine Stratus Forecast System Documentation," MIT Lincoln Laboratory, November 29, 2004

questions of where, when, and how to implement a GDP. For example, whereas FSM provides only information about the possible ground delays associated with a program, a new tool can forecast the airborne delays, as well.

In Chapter Four, the calculations used in the new analytical tool will be detailed. In particular, there are three main differences between the tool and FSM. First, the tool uses a simple, first-come-first-served queue to model the actual flight arrival process and account for the possibility of airborne delays. Second, the tool models the arrival process with a set of distinct arrival capacity rate profiles to consider the arrival capacity uncertainty. Each profile is modeled separately from the perspective of the arrival process. Third, the tool incorporates dynamic elements such as a "current time" variable, which allows the user to change the flights that have departed and are eligible for control. If additional capacity information may become available, the TM can update forecast information to see how, under a proposed program, the state of the system will change over time.

Chapter 3: Approach and Analysis

Chapters One and Two introduced the concept of a ground delay program and how this traffic management initiative can be used to increase the safety and reduce the financial costs of delays due to excessive demand at an airport. Traffic managers are responsible for designing ground delay programs and must contend with several key tradeoffs that underlie their design. The first tradeoff is that, while GDPs require time to affect airborne delays, the uncertainties in arrival demand and, especially, capacity forecasts significantly increase as forecasts extend further ahead in time. Of the different strategic responses to delays in the NAS, ground delay programs are also the most sensitive to the quality of information available and traffic managers often wait for improved information even though it comes at the expense of additional airborne delay costs. The second tradeoff is to find the appropriate strength of a program; the impetus to design a GDP that neither overcontrols nor undercontrols. In the hours preceding anticipated delays, a traffic manager lacks the perfect information that would lead to the design of a GDP that incurs neither air delay costs nor excessive ground delays – yet the traffic manager must still decide what type and when to implement a program.

Chapter Three suggests ways to improve the information given to traffic managers in the course of the decision-making process and so lead to improved ground delay programs. Not only are more detailed probabilistic weather forecasts incorporated into the information currently presented as part of the FSM software tool, but new analyses are also proposed that assist traffic managers in balancing the key tradeoffs of a program. Section 3.1 provides a brief overview of the underlying tool used to develop these metrics. Next, revised metrics are discussed in three phases: first, Section 3.2, the addition of static, probabilistic capacity forecasts to existing metrics; second, Section 3.3, the proposal of new metrics currently beyond the scope of consideration; and, third, Section 3.4, the proposal of how to begin the incorporation of more dynamic, probabilistic forecasts into the design of ground delay programs. Section 3.5 concludes the discussion and transitions to Chapter Four, where the calculations of the underlying model are discussed in greater detail.

Section 3.1: Model Basics

The objective of this research is to improve the quality of information used to develop a ground delay program by proposing new metrics that incorporate probabilistic arrival capacities. To approach this task, a model was developed in Microsoft Excel (herein referred to as "the tool") for a hypothetical airport system[20]. Provided with a capacity scenario, or a complete set of capacity profiles, the tool is designed to, otherwise, mirror the functionality of FSM in creating a GDP, assigning delays, and projecting the arrival times of flights.

Although additional capabilities have been added to the tool to enhance this functionality beyond that of FSM, a key difference underlies the way in which flight delays are handled.

[20] The hypothetical airport system is roughly based on conditions at Chicago O'Hare International Airport so as to achieve some degree of realism in the demand and capacity parameters used

While FSM computes the projected arrival time of a flight based on the capacity profile used for the GDP, the tool uses this profile to construct the GDP and assign demand times *only*[21]. Using these times, the tool then creates a FCFS queue for each of the provided capacity scenarios from which the profile-dependent arrival times can be calculated. This difference will be apparent in the metrics as they are discussed.

For the development of the tool, a sample capacity scenario and flight schedule were used. The capacity scenario (Figure 3-1) contains five different possible profiles that, together, illustrate the arrival of a weather front of uncertain timing and severity. Three refer to the arrival of a weather event of varying magnitude and two additional profiles delay the onset of the storm:

- FC 1: Heavy Rain (40% likelihood)
- FC 2: Light Rain (30%)
- FC 3: No Rain (15%)
- FC 4: Delayed Heavy Rain (10%)
- FC 5: Very Delayed Heavy Rain (5%)

This set of profiles is hypothetical and, although representative of a possible scenario for a large metropolitan airport, is not based on any empirical observations. In keeping with current thinking about probabilistic capacity forecasts, the scenario has five discrete profiles; however, the analyses discussed here can apply to any number of discrete profiles.

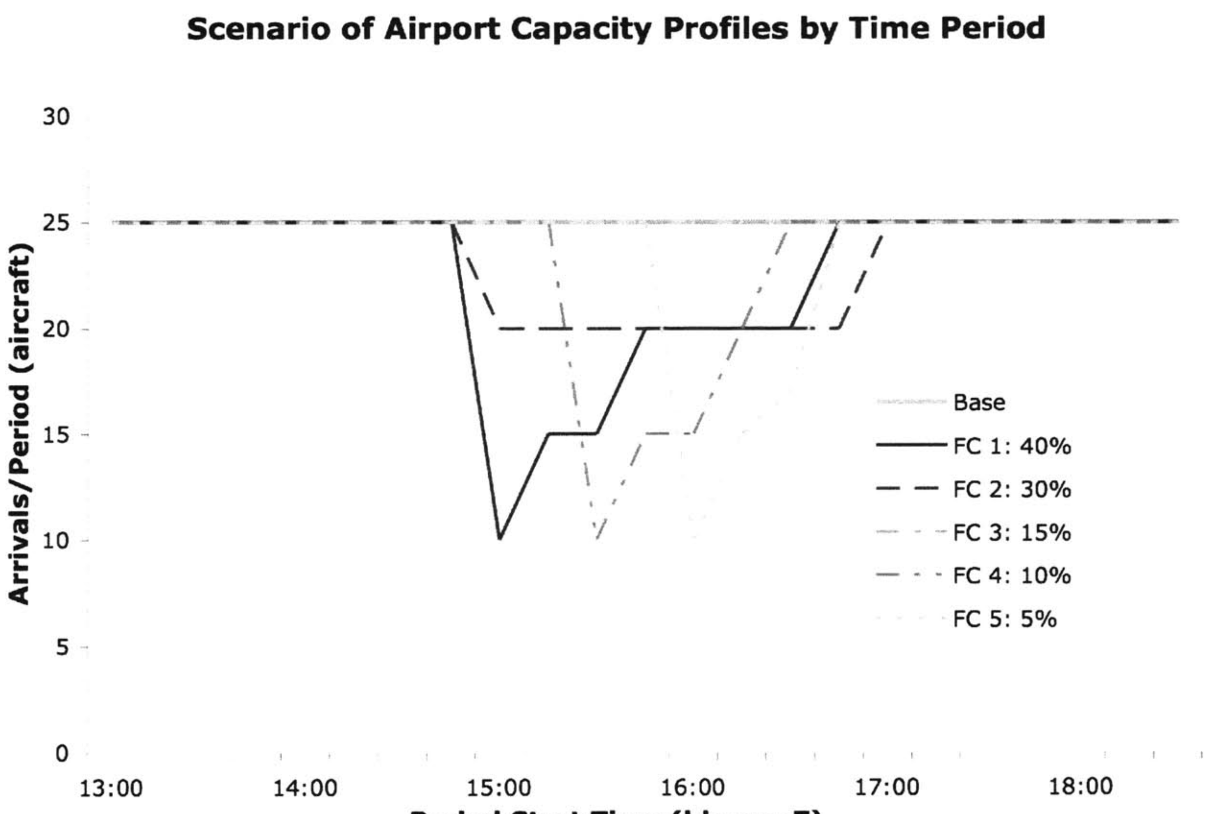

Figure 3-1: Hypothetical scenario of forecast arrival capacity profiles used for the model[22]

[21] This chapter will continue to use the terminology defined in Chapter Two: "arrival" refers to the physical landing of an aircraft and "demand" as the time an aircraft would arrive if not delayed in the air

[22] Each profile shows the maximum number of aircraft arrivals per 15-minute period; "Base" is the nominal capacity

The flight schedule data is a sample set taken from ETMS. The sample data contains a full 24 hours of ETMS-forecasted arrival demand data for Chicago O'Hare International Airport (ORD). This data snapshot was taken at 14:45 Z on June 22, 2005 and contains data between 15:00 Z on the 22nd and 14:59 Z on June 23rd. Please refer to Figure 3-2 for a sample of this data set[23]. Actual ETMS arrival forecasts were used because arrival data is inherently more complicated than that for capacity. ETMS data contains a mix of flights by type, origination, and, if applicable, commercial carrier, that are en route, on the ground, with a filed flight plan, or from the OAG schedule database. Furthermore, actual flight demand data captures the non-random nature of demand, whereby the cyclical peaks and valleys of demand will impact the accumulation and assignment of delays – and will help to visualize the benefits offered by this model over FSM.

Sample ETMS Flight Data							
ID	Period	ACID	TYPE	ORIG	ETD	DEST	ETA
0001	22/1500	53A1186	B735	MSY	A1237	ORD	E1500
0002	22/1500	53A111	B752	BDL	A1236	ORD	E1502
0003	22/1500	10A305	CRJ2	ORF	A1304	ORD	E1502
0004	22/1500	47A126	DC93	MSP	A1403	ORD	E1502
0005	22/1500	53A529	A319	BOS	A1216	ORD	E1504
0006	22/1500	01A829	MD82	BDL	A1230	ORD	E1504
0007	22/1500	01A311	MD83	LGA	A1252	ORD	E1504
0008	22/1500	10A321	CRJ2	RDU	A1319	ORD	E1504
0009	22/1500	01A548	MD82	TUL	A1335	ORD	E1505
0010	22/1500	27A310	B733	AEX	A1303	ORD	E1507
0011	22/1500	50A6808	CRJ2	MBS	A1408	ORD	E1507
0012	22/1500	53A379	B733	CLT	A1336	ORD	E1508
0013	22/1500	10A749	CRJ2	HPN	A1302	ORD	E1509
0014	22/1500	20A1746	B738	IAH	A1307	ORD	E1510
0015	22/1500	28A963	CRJ7	LIT	A1342	ORD	E1510
0016	22/1500	20A1175	B735	EWR	A1301	ORD	E1511
0017	22/1500	01A643	MD82	BOS	A1247	ORD	E1512
0018	22/1500	10A803	CRJ2	ABE	A1334	ORD	E1512
0019	22/1500	53A945	B772	EDDF	A0643	ORD	E1513
0020	22/1500	48A46	B744	ATL	A1351	ORD	E1514
	...						

Figure 3-2: Sample of flight arrival demand data used for the model; ORD June 22nd - 23rd [24]
Period is the time period for the scheduled arrival and is expressed as Day/Time
ACID is the Aircraft ID; Orig is the airport of origination
ETD/ETA is the estimated time of departure / arrival
Note that for flight times, the prefixes "A" and "E" indicate "actual" and "estimated"

[23] The full ETMS data set used for the examples shown in this thesis is contained in Appendix 1A as Figure A1A-1.
[24] Please note that the three-letter operator codes preceding the ACID have been masked by a three-character code (format: ##A)

Section 3.2: Existing Metrics and Static Probabilistic Arrival Capacity Forecasts

The incorporation of probabilistic arrival capacity profiles into existing analyses results in a wide array of metrics, beginning with the simple overall rates of arrival demand and capacity and extending into more complex ones, such as the distributions of both ground and airborne delay that are assigned to flights. Though some metrics are more appealing than others, each offers additional insight to the traffic manager about the impacts of a proposed ground delay program. This section documents the benefits of proposed metrics that either result from the direct incorporation of an arrival capacity *scenario* into the GDP decision process or are based on existing information – but not displayed – in FSM.

Section 3.2.1: Arrival Capacity Profiles

Flight Schedule Monitor currently displays the PAARs that are used as the basis both for the creation of the ground delay program and for arrival time calculations. In Figures 3-3 and 3-4 (both on the following page), the cumulative arrival demand is shown in 15-minute increments in comparison to the five arrival capacity profiles[25] associated with FC 1 through FC 5. For comparison, two additional profiles are shown: "base" indicates the nominal arrival capacity of the airport under ideal atmospheric conditions and "exp" is the expected value, or weighted average, of the different forecasts. In Figure 3-4, the arrival demand has been adjusted by the GDP to reflect the PAARs (shown by the dark, heavy line and marked as "GDP"), which were arbitrarily selected between the best (FC 3) and worst (FC 1) case outcomes.

The inclusion of both arrival capacity and demand on a single chart, allows the traffic manager to compare the proposed GDP profile with the different possible outcomes as well as the actual flight demand. This comparison shows the TM where a GDP may be insufficient / excessive for the capacity scenario so that the program can be adjusted, if necessary. For the example used in this discussion, the proposed GDP is a combination of the severity and timing of the first two, most likely, capacity forecasts. This proposed GDP is used throughout Chapter Three for illustration purposes.

Comparing the two figures, the arrival demand shown in Figure 3-3 is the scheduled arrival demand for the airport while in Figure 3-4 demand rates have been reduced to reflect the PAARs. Under this hypothetical scenario, the traffic manager can compare the charts and see that the proposed GDP in Figure 3-4 shifts demand to comply with the proposed rates. Note that, due to fluctuations in demand within the periods and flight exemptions, the resulting actual demand during a period may be less or greater than the PAAR, even under the ground delay program. With these figure, the traffic manager can answer four important questions using the arrival demand and capacity profile graphs:

1. For which profiles, when, and by how much is capacity insufficient?
2. How do the PAARs compare to the different possible capacity profiles?
3. Does the proposed ground delay program shift demand to be within the capacities of different profiles?
4. How do different, proposed ground delay programs shift demand?

[25] Each profile is a set of forecast airport arrival acceptance rates (FAARs)

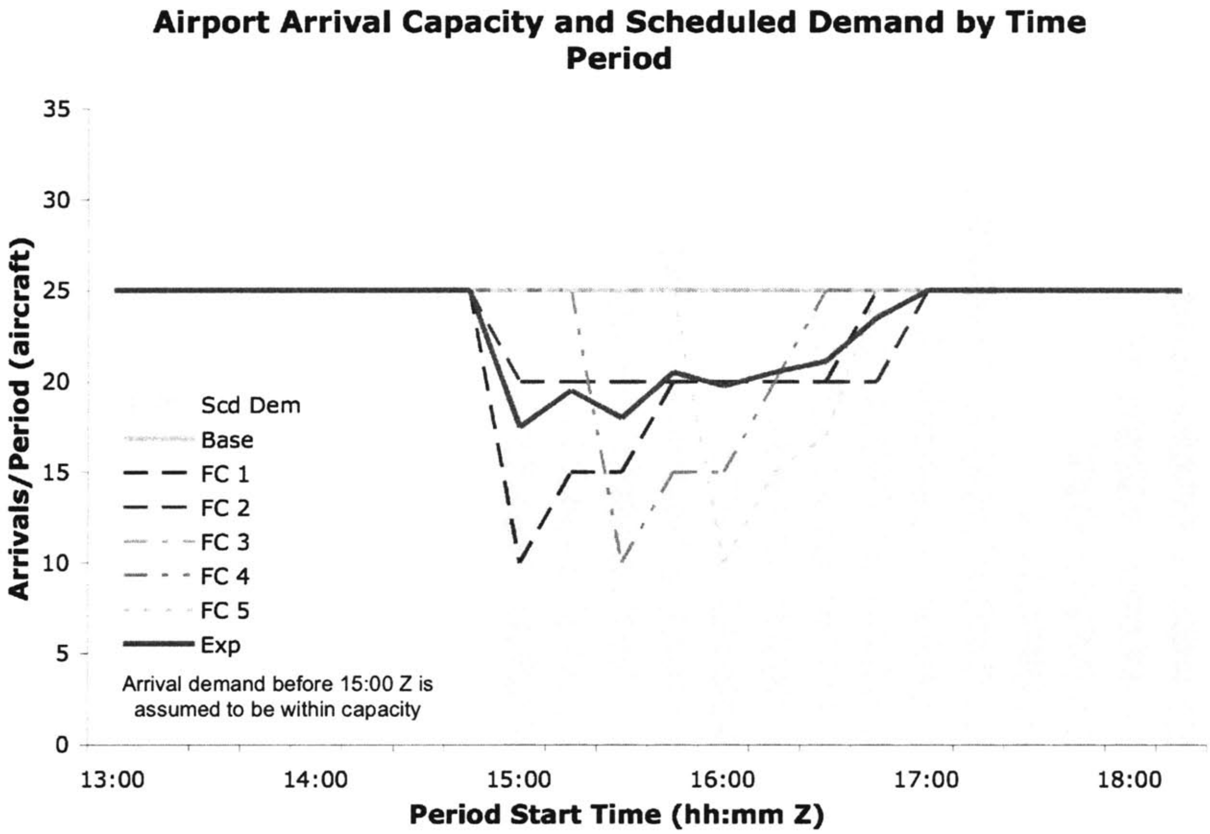

Figure 3-3: Arrival capacity, FAAR profiles, and forecast arrival demand without a GDP

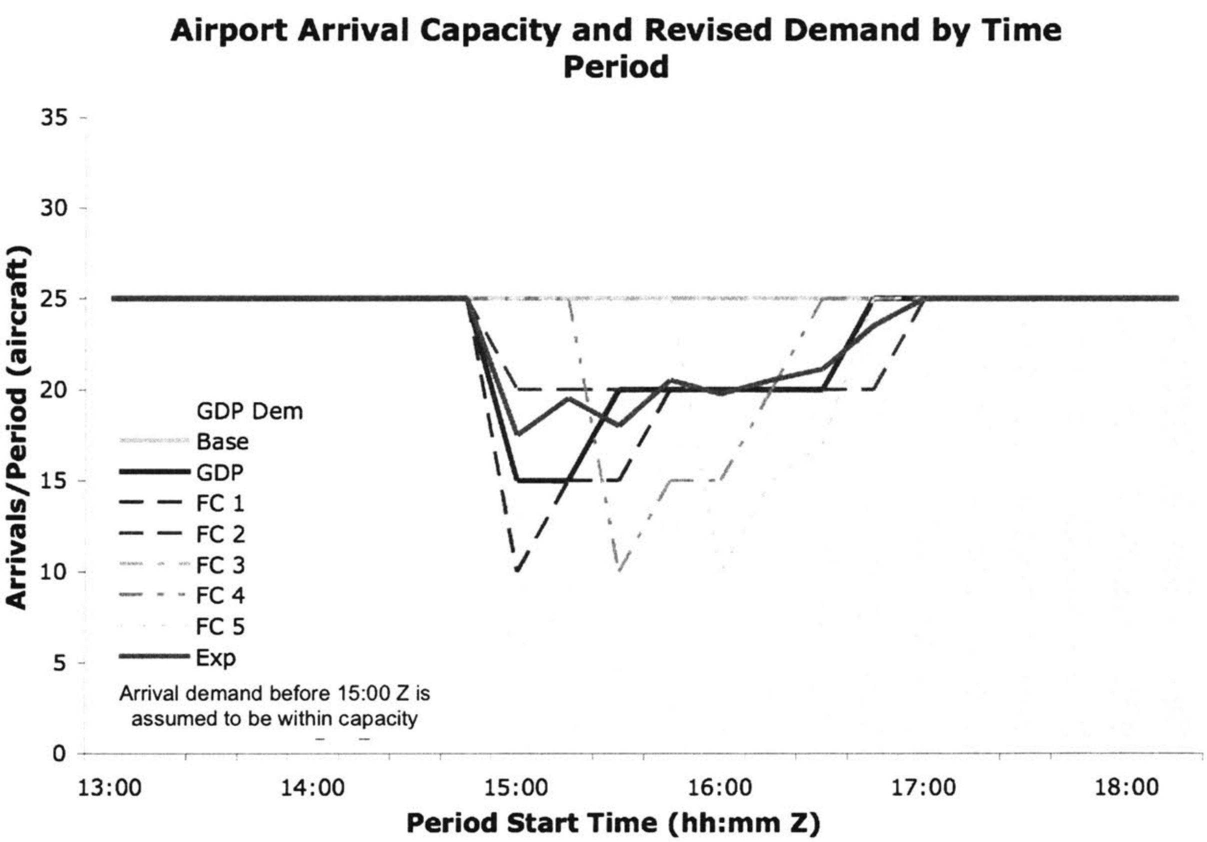

Figure 3-4: Arrival capacity, FAAR profiles, and forecast arrival demand with a GDP

Section 3.2.2: Assigned Ground Delays

Both FSM and the tool assign ground delay to flights by working backward from the slots derived from the PAARs. The number of flights that will experience ground delay over time is shown in Figure 3-5[26]. Although FSM calculates the accumulation of ground delay over time[27], it does not provide information on how these delays are assigned to flights. The tool improves on FSM by creating flight delay summary tables to help understand the distribution of delays and the equity of a proposed program.

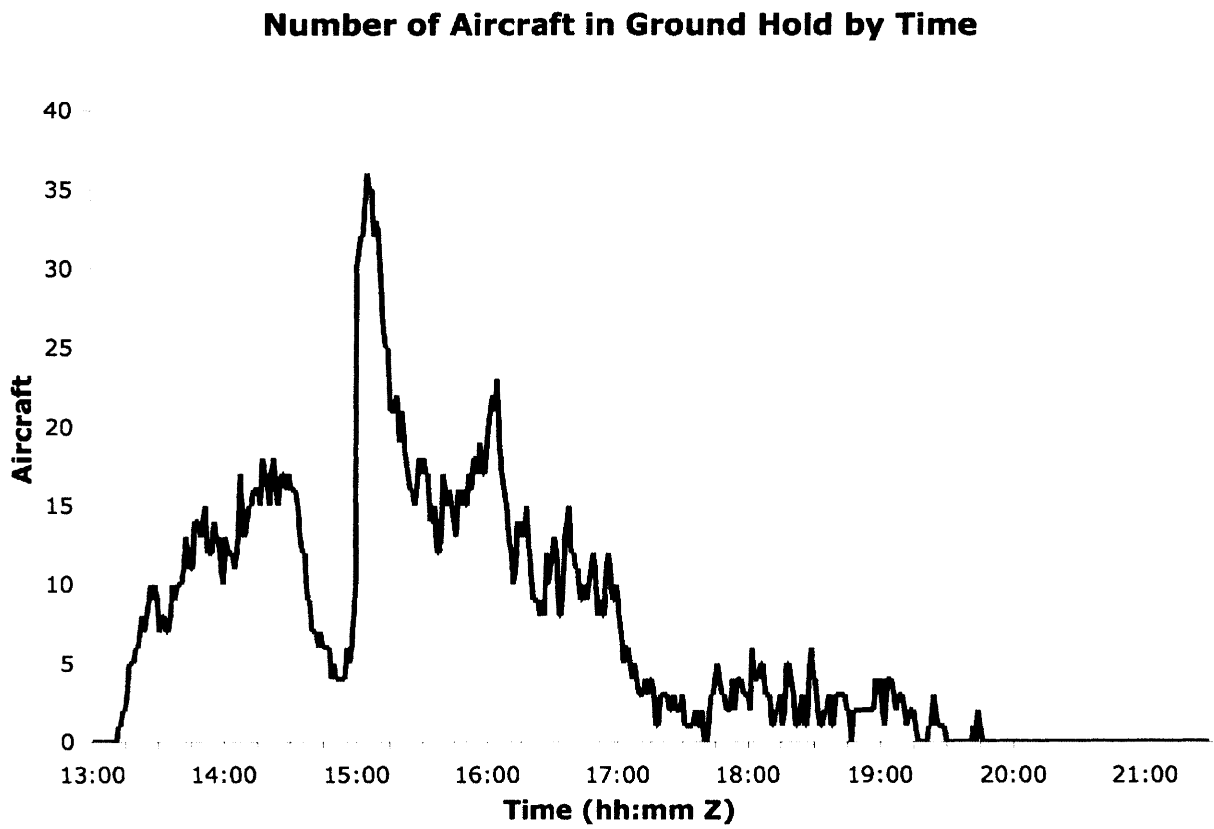

Figure 3-5: Aircraft in ground hold over time for the proposed GDP

In particular, Figure 3-6 is a statistical summary of ground delays and Figure 3-7 is a histogram of assigned ground delay. These two figures allow the traffic manager to see how delays are distributed and how wide / narrow the distribution is. Over the course of a GDP, however, as the number of flights being delayed varies, the amount of ground delay assigned per flight is also expected to change over time. As a result, equity, or fairness, is not necessarily maximized when the distribution of assigned delay is concentrated within a narrow range, or delay is assigned equally.

[26] For more information on the ground delays calculated by the tool, please see §4.3.2
[27] Previously discussed as "unrecoverable delay" in §2.3.3

Ground Delay Summary Statistics				
	Scheduled Demand Time	Ground Delay (Incl. Flights)	Ground Delay (All Flights)	Demand Time With Program
Min	15:00 Z	00:00	00:00	15:00 Z
Mean	17:44 Z	00:07	00:07	17:52 Z
Max	20:29 Z	00:19	00:19	20:29 Z
Spread	05:29	00:19	00:19	05:29
StDev	01:34	00:05	00:05	01:30
Coeff Var.	11.29	1.38	1.20	11.79
Total		58:06	58:06	
Total Flights	487	439	487	487
+/- 1 StDev	274	220	248	285
+/- 2 StDev	487	439	487	487

All time is displayed in hh:mm format
Min, Mean, Max are the minimum, expected value, and maximum of flight delays
Spread is Max - Min
The coefficient of variation is defined as Mean/StDev and is unitless
+/- StDev refers to the number of flights within a standard deviation of the mean
Flight counts are expressed in number of aircraft

Figure 3-6: Ground delay summary statistics

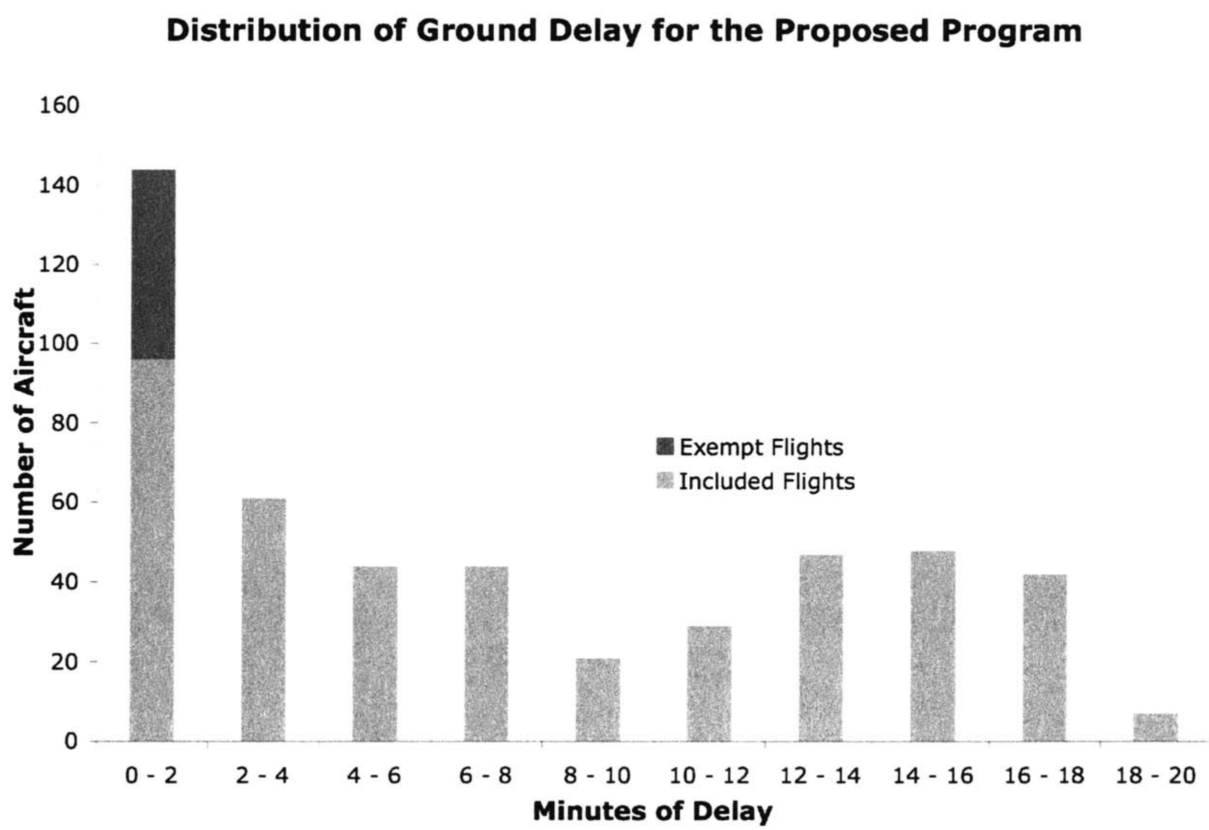

Figure 3-7: Histogram of assigned ground delays by flight

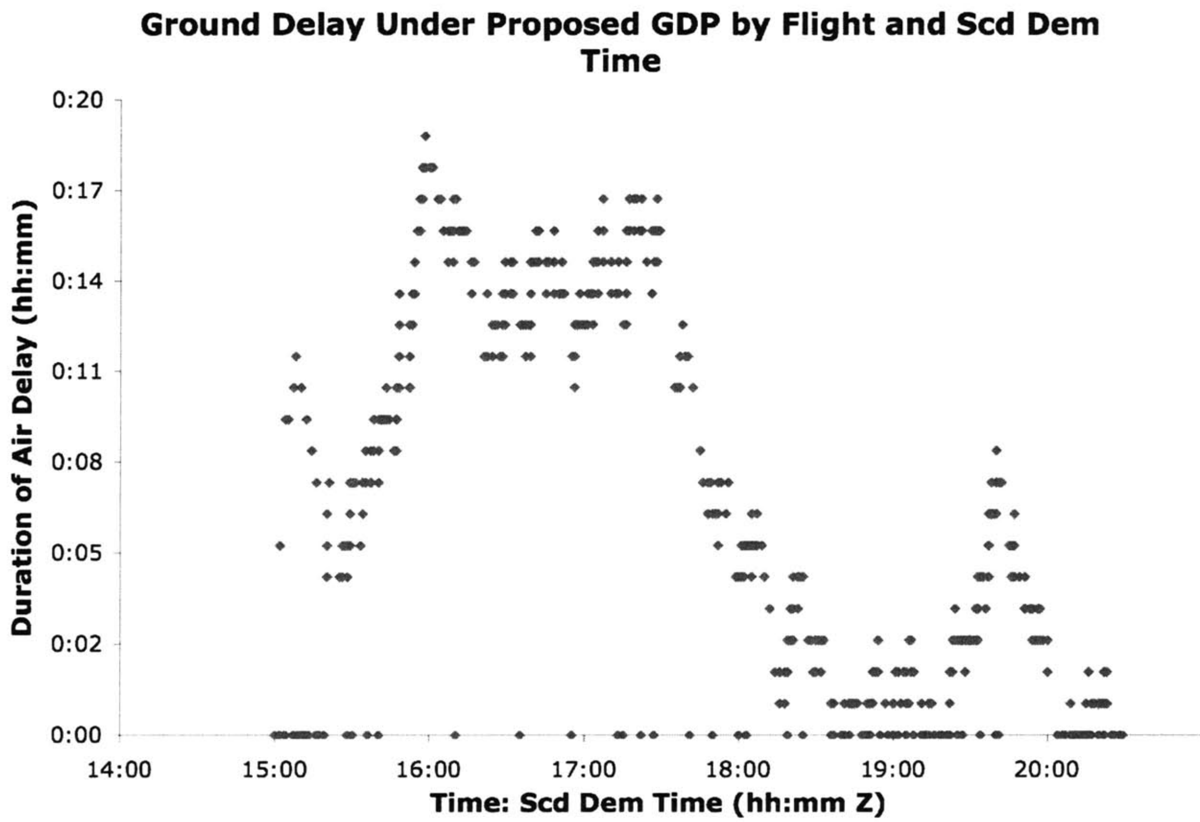

Figure 3-8: Assigned ground delay by scheduled flight arrival time

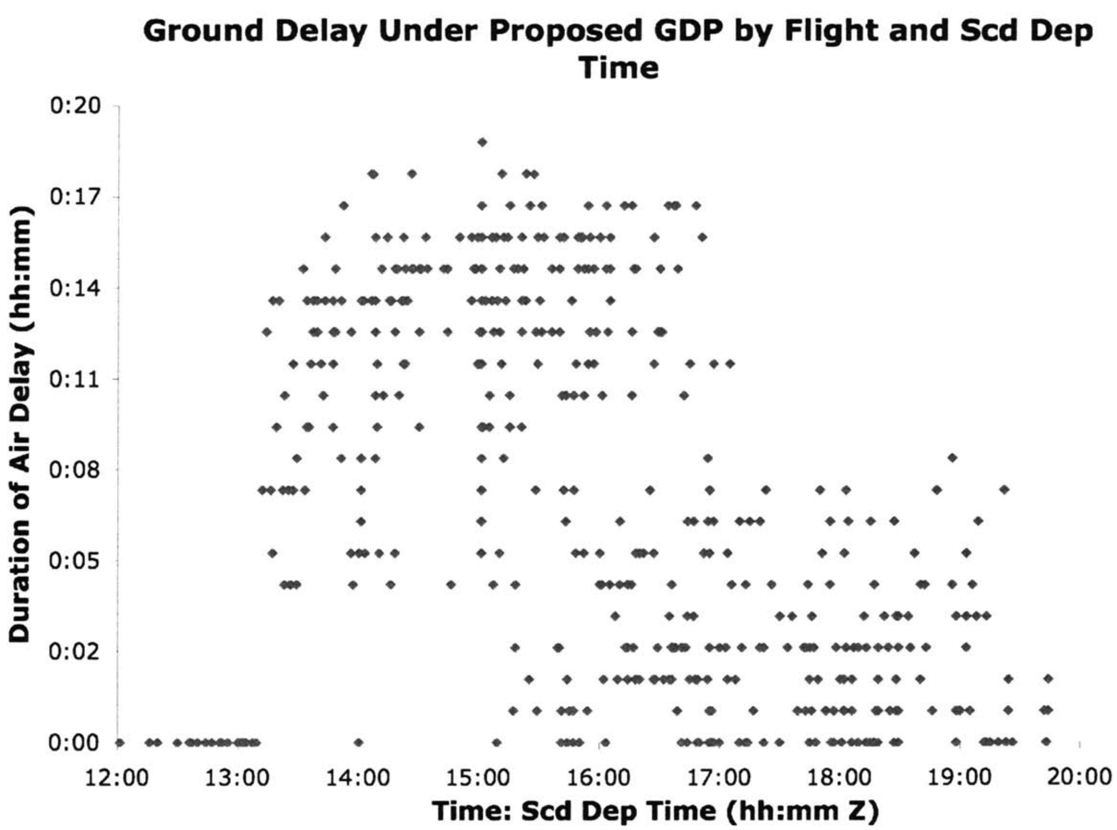

Figure 3-9: Assigned ground delay by scheduled flight departure time

The overall distribution of delay is only one tool of many that can be employed by the traffic manager to understand the equity of a program. Additional charts, Figures 3-8 and 3-9, show the assigned delay by scheduled arrival time and departure time, respectively. Although exemptions and differing departure times greatly complicate equity considerations, visual inspection of these charts will allow a traffic manager to perform an outlier analysis, identifying flights with unusually large assigned delays relative to other flights with similar scheduled arrival / departure times.

Together, figures 3-5 through 3-9 help address several important questions, including:

1. How many flights are engaged in a ground delay over time?
2. What is the distribution of ground delays among flights?
3. Are there any flights that receive an unusually large assigned ground delay?
4. What is the maximum ground delay of any flight?
5. What is the average ground delay of all flights and of only those flights included in the program?

Section 3.2.3: Airborne Queues and Arrival Times

FSM treats arrival times as being equivalent to the slot times specified by the PAARs provided by the TM. This methodology assumes that any air delays that do occur are limited to flights that are not controlled by the program – flight exemptions – and, as such, airborne delays are not relevant to the GDP decision process. However, when different possible arrival capacity profiles can be realized, flights that are included in a ground delay program may also face possible delays in the air before arrival. To calculate these possible air delays, the projected arrival times, or occupied slots, for each of the possible capacity outcomes must first be imputed. Although later sections will explore these airborne delays, the arrival times, themselves, offer useful information for both traffic managers and airline operators.

The incorporation of uncertainty about arrival capacities is shown in Figures 3-10 through 3-12, which illustrate the number of arrivals and size of the airborne arrival queues by time. Rather than reflect the arrivals for specific flights, these cumulative results simply track the number of aircraft that are assigned to arrival slots prior to a given time, such that the assigned slot time is greater than or equal to the demand time. Figure 3-10 is a table of the number of

Airborne Queue by Capacity Profile

Time Period	Additional Demand	Airborne Queue FC 1	FC 2	FC 3	FC 4	FC 5
15:00	14	5	0	0	0	0
15:15	15	5	0	0	0	0
15:30	20	10	0	0	10	0
15:45	20	10	0	0	15	0
16:00	20	10	0	0	20	10
16:15	20	10	0	0	20	15
16:30	20	10	0	0	15	18
16:45	25	10	5	0	15	18
17:00	25	10	5	0	15	18
17:15	25	10	5	0	15	18
17:30	25	10	5	0	15	18
17:45	25	10	5	0	15	18
18:00	25	10	5	0	15	18
18:15	25	10	5	0	15	18
18:30	21	6	1	0	11	14
18:45	23	4	0	0	9	12
19:00	25	4	0	0	9	12
19:15	21	0	0	0	5	8
19:30	25	0	0	0	5	8

Demand, queue are expressed in number of aircraft
The start time is shown for each period as hh:mm Z

Figure 3-10: Arrival queue size after each time period

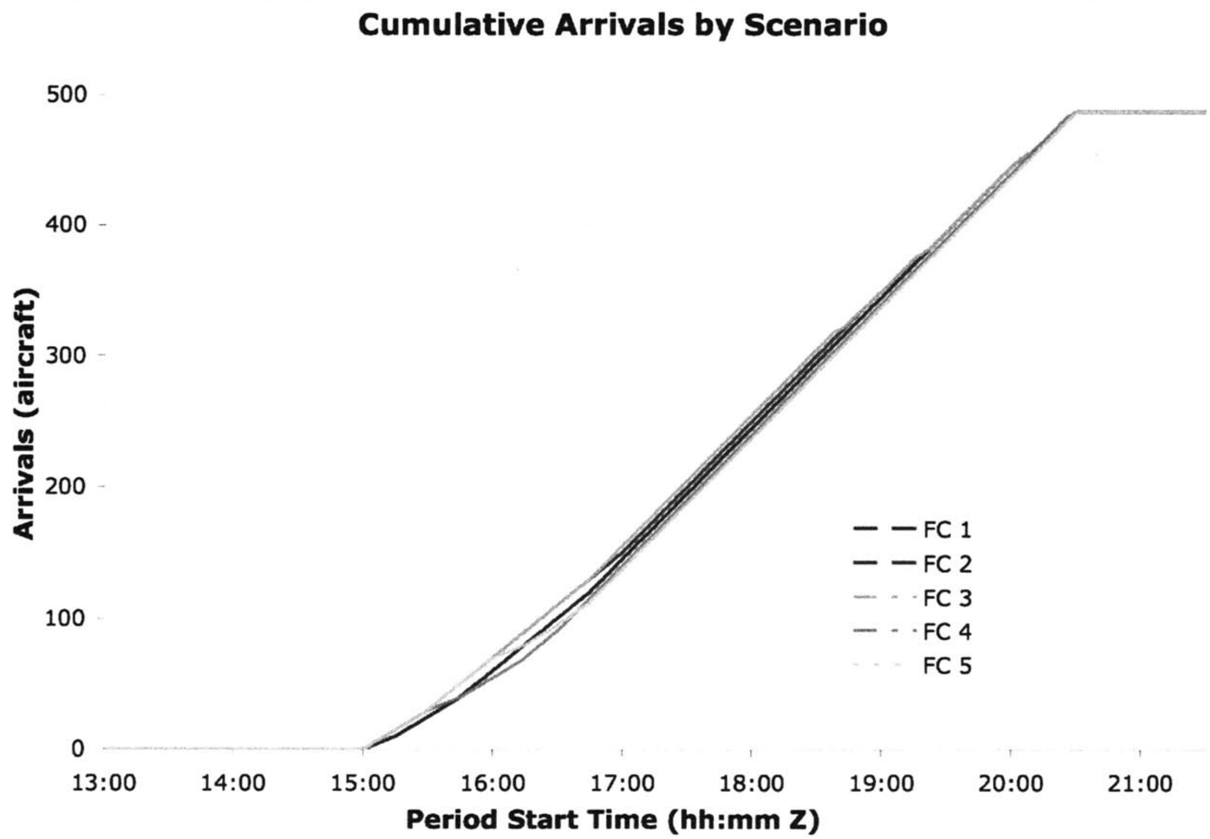

Figure 3-11: Cumulative arrivals by minute

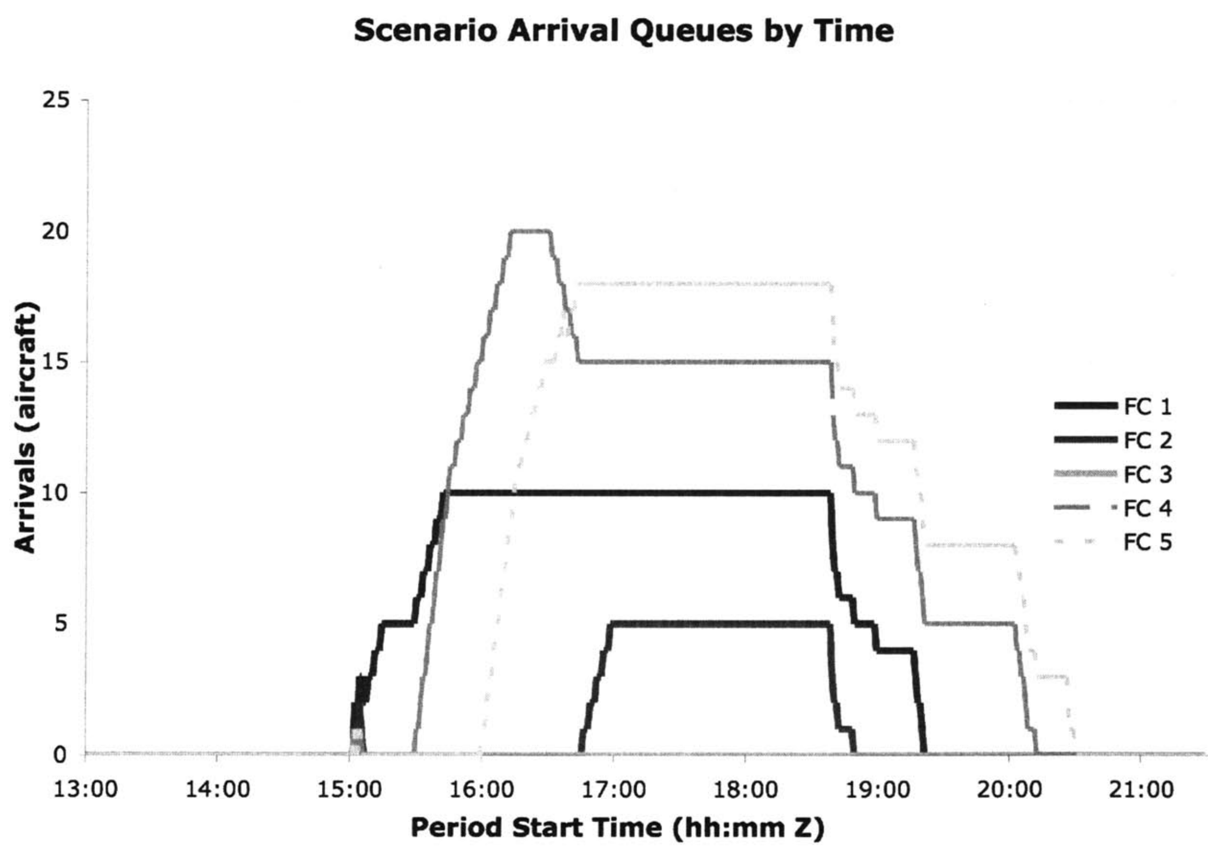

Figure 3-12: Airborne Arrival Queue (Stack Size) by Minute

arrivals during each 15-minute period and aircraft in the airborne queue (unsatisfied demand) for each outcome at the end of each period. In Figures 3-11 and 3-12, the cumulative arrivals and total queue size for each outcome is shown with one-minute resolution. In conjunction with the arrival capacity profiles (Figure 3-1), these charts illustrate how a brief storm can cause airborne delays that persist for hours at a busy airport.

Arrival queue forecasts provide the traffic manager with two key pieces of information. Directly, projected queue sizes help avoid potential trouble spots when the queue size could exceed standards for safety or generate excessive financial costs. For example, in Figure 3-12, the queues for both FC 4 and FC 5 exceed 15 aircraft. Indirectly, arrival queues are an indicator of whether or not a proposed program is too relaxed, part of the second key tradeoff: when, by how much, and under which scenarios the proposed program is insufficient to prevent lengthy airborne delays. As shown, the proposed GDP may not be strict enough to prevent all of the delays that can occur due to four of the five possible outcomes (85% cumulative likelihood). Categorically, total arrivals and overall queue size can be used to evaluate the following questions:

1. How does the expected queue size vary by time?
2. Does the queue ever exceed a maximum allowed value?
3. Which capacity profiles result in the largest queues and at what times?
4. How do the queue sizes of the proposed program and their likelihoods compare to other possible programs?

Scheduled and Proposed Arrival Order by Flight

	Arrival Order	
Flight ID	Scheduled	Proposed
53A1186	1	1
53A111	2	2
10A305	3	3
47A126	4	8
53A529	5	4
01A829	6	5
01A311	7	6
10A321	8	14
01A548	9	15
27A310	10	7
50A6808	11	18
53A379	12	20
10A749	13	9
20A1746	14	10
28A963	15	21
20A1175	16	11
01A643	17	12
10A803	18	22
53A945	19	13
48A46	20	23
...		

Figure 3-13: Demand and arrival order by profile

Under the basic assumption that airborne arrival queues are processed in FCFS order, the demand times calculated by FSM can be used to forecast arrival times for specific flights based on the different capacity profiles. The table shown as Figure 3-13 contains the original scheduled and proposed demand and arrival orders by flight. While both use FCFS to determine arrival order, the order for the GDP will differ as delays are only assigned to flights that are included in the program. By viewing this figure, a TM can see how the flight arrival order will change given the proposed ground delay program or as compared to other proposed programs.

The table in Figure 3-14 illustrates demand and, for each profile, arrival times for individual flights. Specified by flight, projected arrival times are of greater use to airline operators, who can use this information to plan for ground operations and revise flight schedules. For the traffic manager, flight arrival times can be used to answer:

1. At what times will specific flights arrive for each profile?
2. How does flight arrival order change when implementing the GDP?
3. What is the likelihood of a specific flight arriving before or after a certain time?

Flight Demand and Arrival Times by Outcome							
	Demand			Flight Arrival Time			
Flight ID	Time	Exp	FC 1	FC 2	FC 3	FC 4	FC 5
53A1186	15:00	15:00	15:00	15:00	15:00	15:00	15:00
53A111	15:02	15:02	15:03	15:02	15:02	15:02	15:02
10A305	15:02	15:03	15:04	15:03	15:03	15:03	15:03
47A126	15:08	15:09	15:12	15:08	15:08	15:08	15:08
53A529	15:04	15:04	15:06	15:04	15:04	15:04	15:04
01A829	15:04	15:05	15:07	15:05	15:04	15:04	15:04
01A311	15:04	15:06	15:09	15:06	15:05	15:05	15:05
10A321	15:14	15:16	15:19	15:14	15:14	15:14	15:14
01A548	15:15	15:17	15:20	15:15	15:15	15:15	15:15
27A310	15:07	15:08	15:10	15:07	15:07	15:07	15:07
50A6808	15:18	15:20	15:23	15:18	15:18	15:18	15:18
53A379	15:20	15:22	15:25	15:20	15:20	15:20	15:20
10A749	15:09	15:10	15:13	15:09	15:09	15:09	15:09
20A1746	15:10	15:12	15:15	15:10	15:10	15:10	15:10
28A963	15:21	15:23	15:26	15:21	15:21	15:21	15:21
20A1175	15:11	15:13	15:16	15:11	15:11	15:11	15:11
01A643	15:12	15:14	15:17	15:12	15:12	15:12	15:12
10A803	15:22	15:24	15:27	15:22	15:22	15:22	15:22
53A945	15:13	15:15	15:18	15:13	15:13	15:13	15:13
48A46	15:23	15:25	15:28	15:23	15:23	15:23	15:23
...							

Time is expressed in hh:mm Z

Figure 3-14: Projected flight demand and arrival times by outcome

Section 3.2.4: Arrival Delays

Under the "PAAR-defined slot times are the arrival times" methodology of FSM, airborne delays are neither forecasted nor presented to the traffic manager. Once the specific flight arrival times have been found for each capacity profile, however, airborne delays become a measurable possibility and can be calculated as the difference between flight demand and arrival times. Both the total amount of airborne delay and delay by flight provide valuable information to the design process of a GDP. After all, in essence, a GDP is built to prevent airborne delay. By illustrating the different types of delay, the traffic manager can understand the benefits of the ground delay program and compare it to a) not instituting a program and b) instituting an alternative program. Except where noted, the examples contained in this chapter all refer to delays that will occur assuming implementation of the proposed GDP – for illustrations of delays without a GDP, please refer to Appendix 1C.

Cumulative Arrival Delays

The first level of analysis of delay is to examine the cumulative delay for a program. In Figures 3-15 and 3-16, the accumulation of airborne delay in the system is plotted over time for the different capacity profiles. Note that, for the proposed GDP, the worst-case outcome (FC 5) results in more than 3,500 minutes of airborne delays, with a majority of the delay accumulating between 16:00 Z and 17:00 Z (Figure 3-15). In comparison, without a program (Figure 3-16), the worst-case profiles are FC 1 and FC 4, each of which result in more than 5,000 minutes of airborne delay. The expected airborne delays are reduced by more than 50% overall because of the program. From these numbers, one could conclude that the GDP is beneficial. However, further examination shows that the amount of airborne delay for FC 5 actually *increases* as a result of the GDP because of the postponement of earlier arrivals when, for FC 5, the weather is clear until the storm arrives. The risk posed by FC 5 to a proposed program is only apparent when the result of each possible capacity profile is identified.

A second metric, Figure 3-17, shows total delay accumulation, which includes proposed ground delay. In this example, all ground delay occurs before the accumulation of air delay; correspondingly, all capacity profiles exhibit the same initial accumulation of delay. A further comparison of Figures 3-16 and 3-17 helps answer four important questions:

1. What is the overall expected airborne / total delay of the proposed program?
2. What is the airborne / total delay for each of the outcomes?
3. Which outcomes result in the largest cumulative airborne / total delays?
4. For each outcome, how does the rate of airborne / total delay accumulation vary over time?

As shown, implementing the GDP actually adds 1,000 minutes to the total expected delay. It is difficult to compare total delay accumulation with and without the GDP, however, because the types of delay have changed between air and ground. Methods of comparing different delay types will be discussed in §3.3.2.

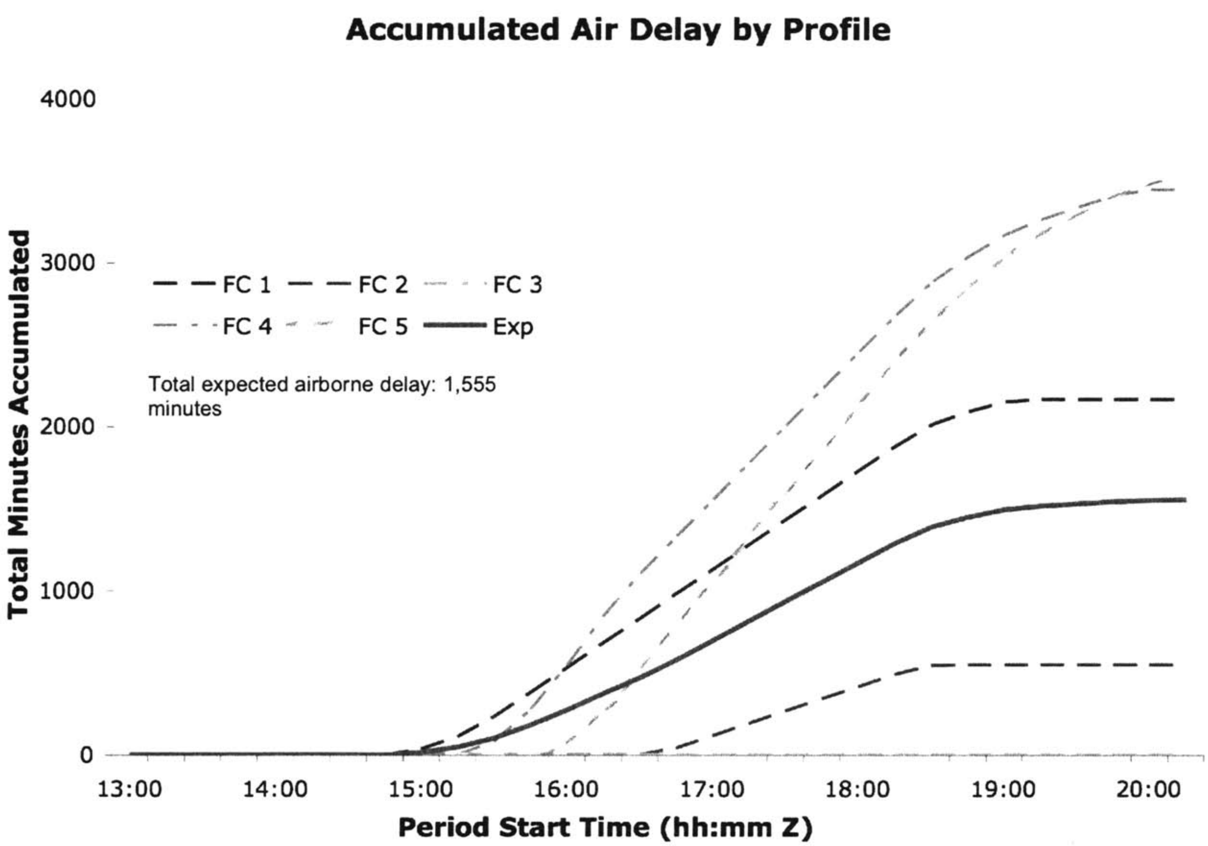

Figure 3-15: Cumulative airborne delays

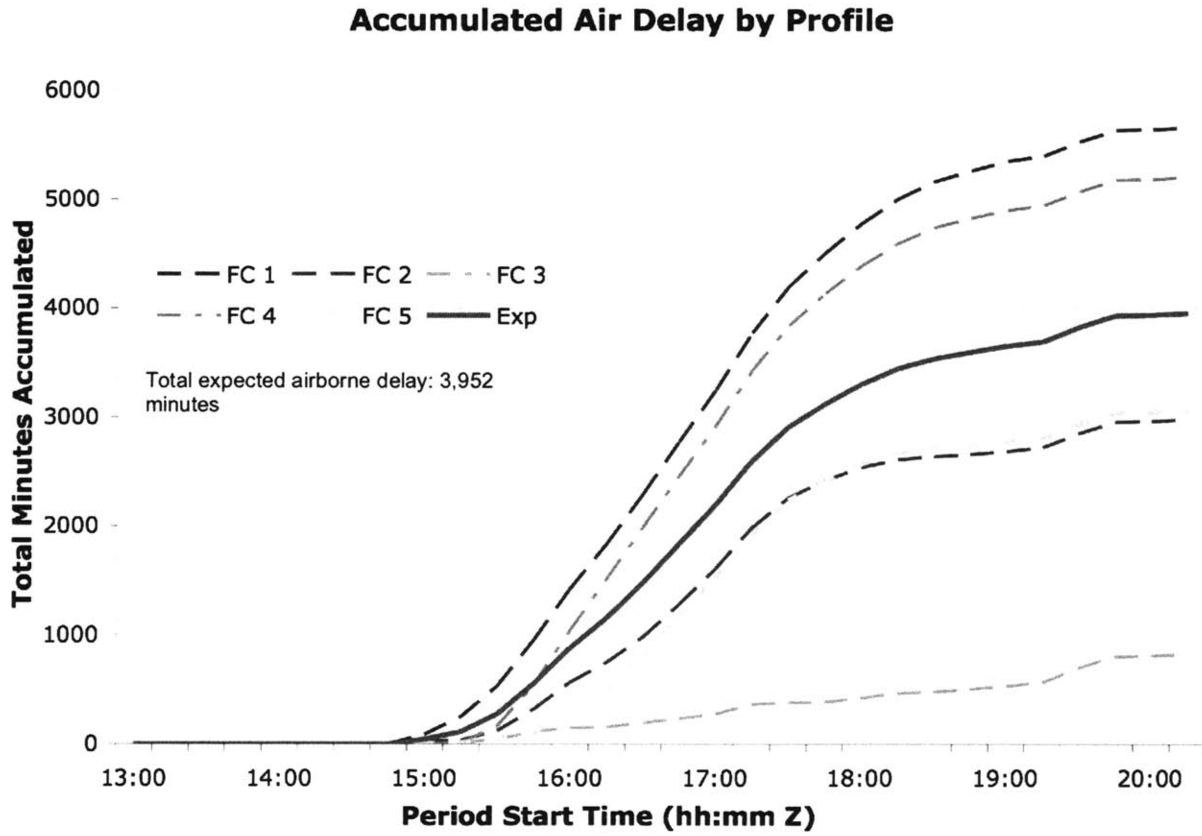

Figure 3-16: Cumulative airborne delays without a GDP

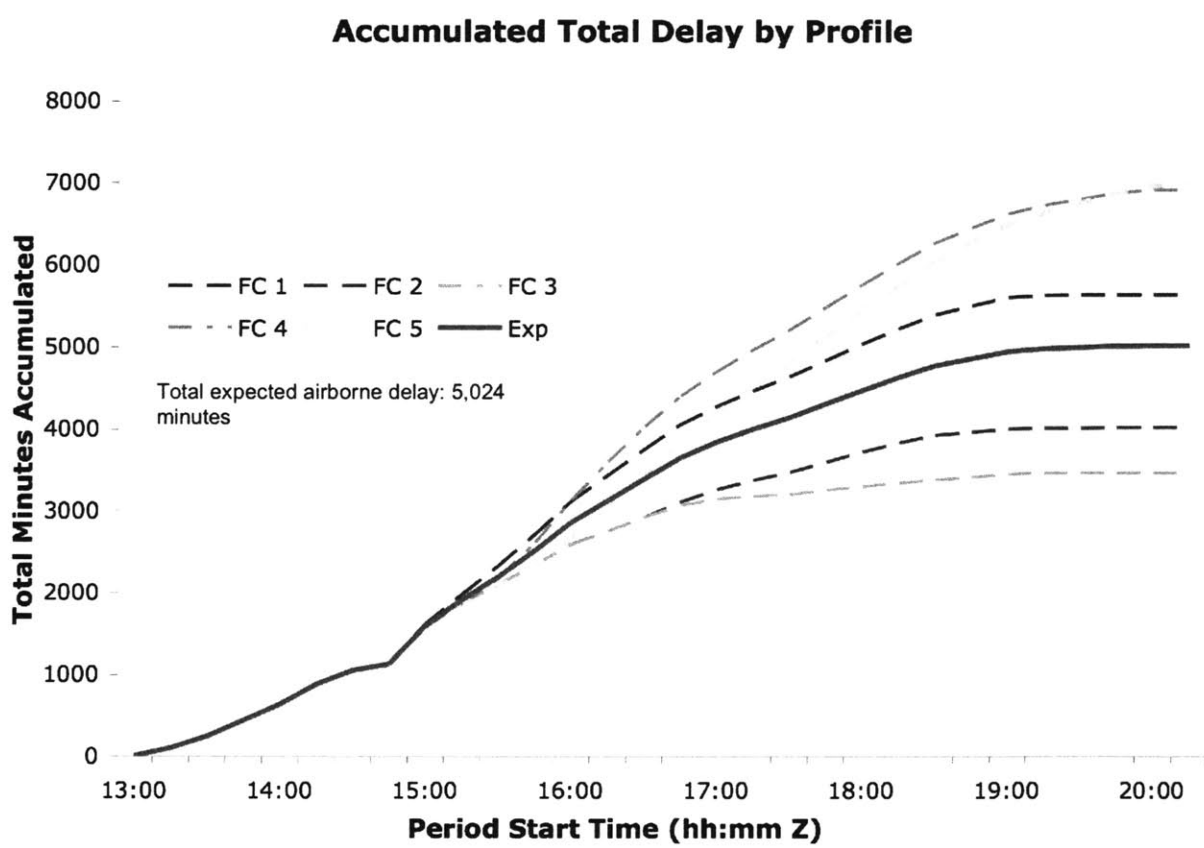

Figure 3-17: Cumulative total delays

Arrival Delays by Flight

A more detailed analysis examines how delays are allocated among flights, leading towards two important measures. First, a traffic manager will want to examine the likelihood of large airborne delays to individual flights, those that might result in aircraft running low on fuel and diverting to a different arrival airport. The excessive cost of network and travel disruption to operators and passengers makes diversions very undesirable. The expected number of diversions can be calculated using airborne flight delay durations and a function of the likelihood of diversion by delay duration[28].

Flight Ground and Airborne Delays by Outcome

	Ground	Airborne Delay					
Flight ID	Delay	Exp	FC 1	FC 2	FC 3	FC 4	FC 5
53A1186	0:00	0:00	0:00	0:00	0:00	0:00	0:00
53A111	0:00	0:00	0:01	0:00	0:00	0:00	0:00
10A305	0:00	0:01	0:02	0:01	0:01	0:01	0:01
47A126	0:06	0:01	0:04	0:00	0:00	0:00	0:00
53A529	0:00	0:00	0:02	0:00	0:00	0:00	0:00
01A829	0:00	0:01	0:03	0:01	0:00	0:00	0:00
01A311	0:00	0:02	0:05	0:02	0:01	0:01	0:01
10A321	0:10	0:02	0:05	0:00	0:00	0:00	0:00
01A548	0:10	0:02	0:05	0:00	0:00	0:00	0:00
27A310	0:00	0:01	0:03	0:00	0:00	0:00	0:00
50A6808	0:11	0:02	0:05	0:00	0:00	0:00	0:00
53A379	0:12	0:02	0:05	0:00	0:00	0:00	0:00
10A749	0:00	0:01	0:04	0:00	0:00	0:00	0:00
20A1746	0:00	0:02	0:05	0:00	0:00	0:00	0:00
28A963	0:11	0:02	0:05	0:00	0:00	0:00	0:00
20A1175	0:00	0:02	0:05	0:00	0:00	0:00	0:00
01A643	0:00	0:02	0:05	0:00	0:00	0:00	0:00
10A803	0:10	0:02	0:05	0:00	0:00	0:00	0:00
53A945	0:00	0:02	0:05	0:00	0:00	0:00	0:00
48A46	0:09	0:02	0:05	0:00	0:00	0:00	0:00
...							

Time is expressed in hh:mm

Figure 3-18: Sample of air / ground delays by flight

The second implication of the distribution of delays is equity, the fairness of the distribution. In part, information about the distribution of delays elucidates this question; Figure 3-19 includes the standard deviation of airborne delays across flights, as well as a count of those flights that are within the average by one and by two standard deviations. As discussed previously, however, delays tend to fluctuate with time so it may be preferable to compute summary statistics for subsets of flight arrivals, for example, by air carrier, origination airport, flight duration, or, as shown in Figure 3-20, by scheduled arrival time period. In this example,

28 Such a function is beyond the scope of this thesis, but it could likely be found by regressing the occurrence of diversion on the duration of airborne delay and other variables including aircraft type, expected flight duration, etc.

those flights scheduled to arrive at the beginning of the storm will experience similar delays. Although this would seem to be a foregone conclusion, during periods of heavy delays and when a large number of aircraft are exempted from the program, airborne delays can vary noticeably. Important questions that can be addressed with flight-specific arrival and total delays include:

1. What is the largest airborne / total delay of any flight?
2. What is the average total delay of included flights?
3. What is the average total delay of all flights?
4. How are these delays distributed?
5. Do any flights receive large airborne / total delays as compared to others with similar arrival / departure times?

Airborne Delay Summary Statistics						
				Capacity Profile		
	Exp	FC 1	FC 2	FC 3	FC 4	FC 5
Min	0:00	0:00	0:00	0:00	0:00	0:00
Mean	0:03	0:04	0:01	0:00	0:07	0:07
Max	0:05	0:08	0:03	0:01	0:15	0:14
Spread	0:05	0:08	0:03	0:01	0:15	0:14
StDev	0:01	0:02	0:01	0:00	0:04	0:04
Coeff Var.	1.75	1.61	0.80	0.06	1.70	1.72
Total	25:55	36:08	9:13	0:02	57:30	58:56

Total Flights	487	487	487	487	487	487
+/- 1 StDev	355	334	314	485	358	351
+/- 2 StDev	487	487	487	485	487	487

Figure 3-19: Airborne delay summary statistics

Airborne Delay Summary Statistics						
				Capacity Profile		
	Exp	FC 1	FC 2	FC 3	FC 4	FC 5
Min	0:00	0:00	0:00	0:00	0:00	0:00
Mean	0:02	0:04	0:00	0:00	0:00	0:00
Max	0:03	0:07	0:02	0:01	0:06	0:01
Spread	0:03	0:07	0:02	0:01	0:06	0:01
StDev	0:00	0:01	0:00	0:00	0:01	0:00
Coeff Var.	2.81	3.10	0.27	0.23	0.51	0.23
Total	1:20	3:08	0:04	0:02	0:36	0:02

Total Flights	39	39	39	39	39	39
+/- 1 StDev	29	28	36	37	33	37
+/- 2 StDev	37	37	36	37	35	37

All time is displayed in hh:mm format
Min, Mean, Max are the minimum, expected value, and maximum of flight delays
Spread is Max - Min
The coefficient of variation is defined as Mean/StDev and is unitless
+/- StDev refers to the number of flights within a standard deviation of the mean
Flight counts are expressed in number of aircraft

Figure 3-20: Airborne delay summary for aircraft with scheduled arrival times between 15:00 and 15:30 Z

Incorporating Likelihood

Flight delays can also be displayed according to arrival or demand times and likelihood of occurrence. One possible manner of displaying this information is exhibited in Figures 3-21 and 3-22, which show the accumulation of airborne and total delay that results from a program by scheduled arrival time. In both figures, the size of a data point indicates its likelihood of occurring. As shown in Figure 3-21, the most likely outcomes are FC 1 and FC 2; those least likely, but with greater airborne delays are FC 4 and FC 5. For FC 4 and FC 5, the dramatic increases in expected airborne delay at 15:30 and 16:00 Z, respectively, correspond to the decrease in arrival capacities (Figure 3-3) and increase in queue sizes (Figure 3-12) previously illustrated. The advantage of the view shown in Figure 3-21 is that it also shows the likelihood of each outcome occurring.

As there are five profiles, five points represent each flight. This is most clearly seen in Figure 3-22, where concentric data points represent a flight that receives the same amount of overall delay for different scenarios, while vertically dispersed points indicate a flight that receives varying amounts of delay. Furthermore, Figure 3-22 also exhibits the difference between flights that are assigned ground delay and those that are excluded. For example, for FC 5, there are two patterns that emerge. The group with greater total delay is comprised of those flights that receive both air and ground delay, while the group with less total delay was exempt and not assigned any ground delay.

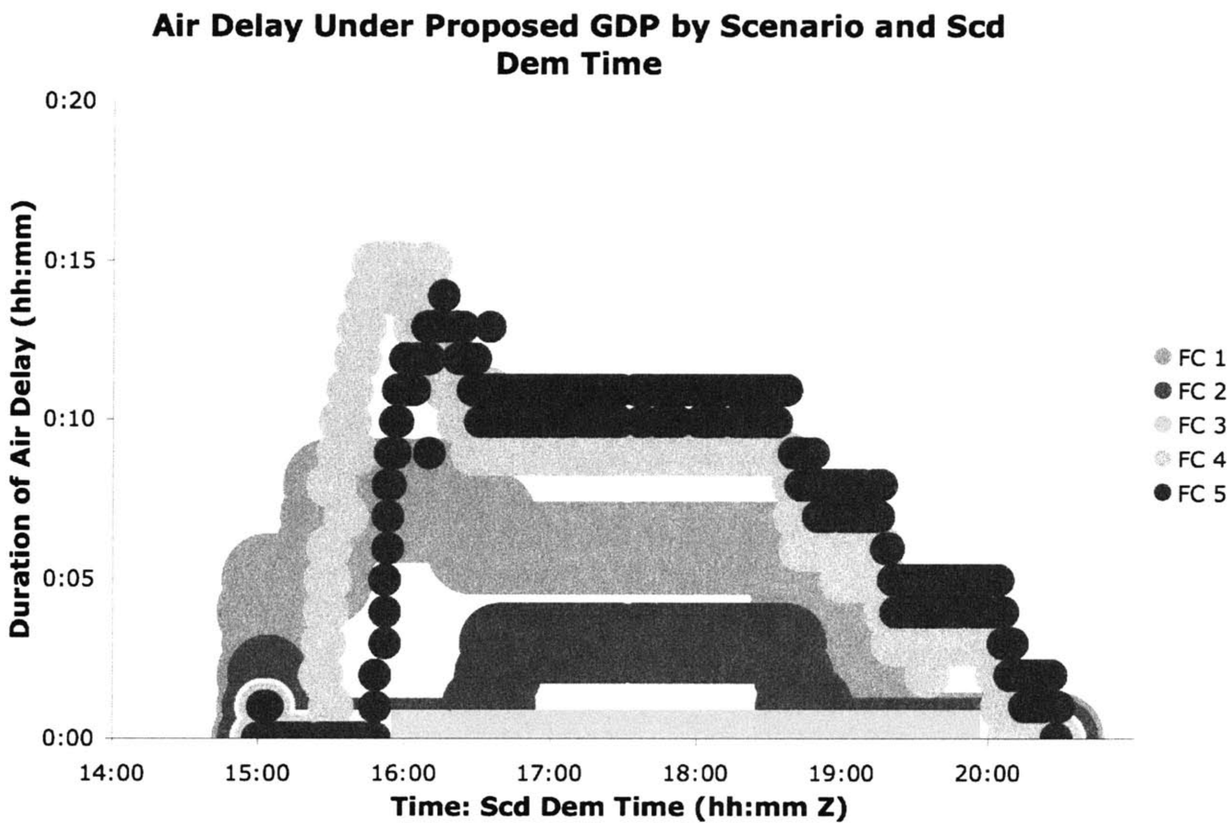

Figure 3-21: Airborne delays by flight and likelihood (by scheduled demand time)

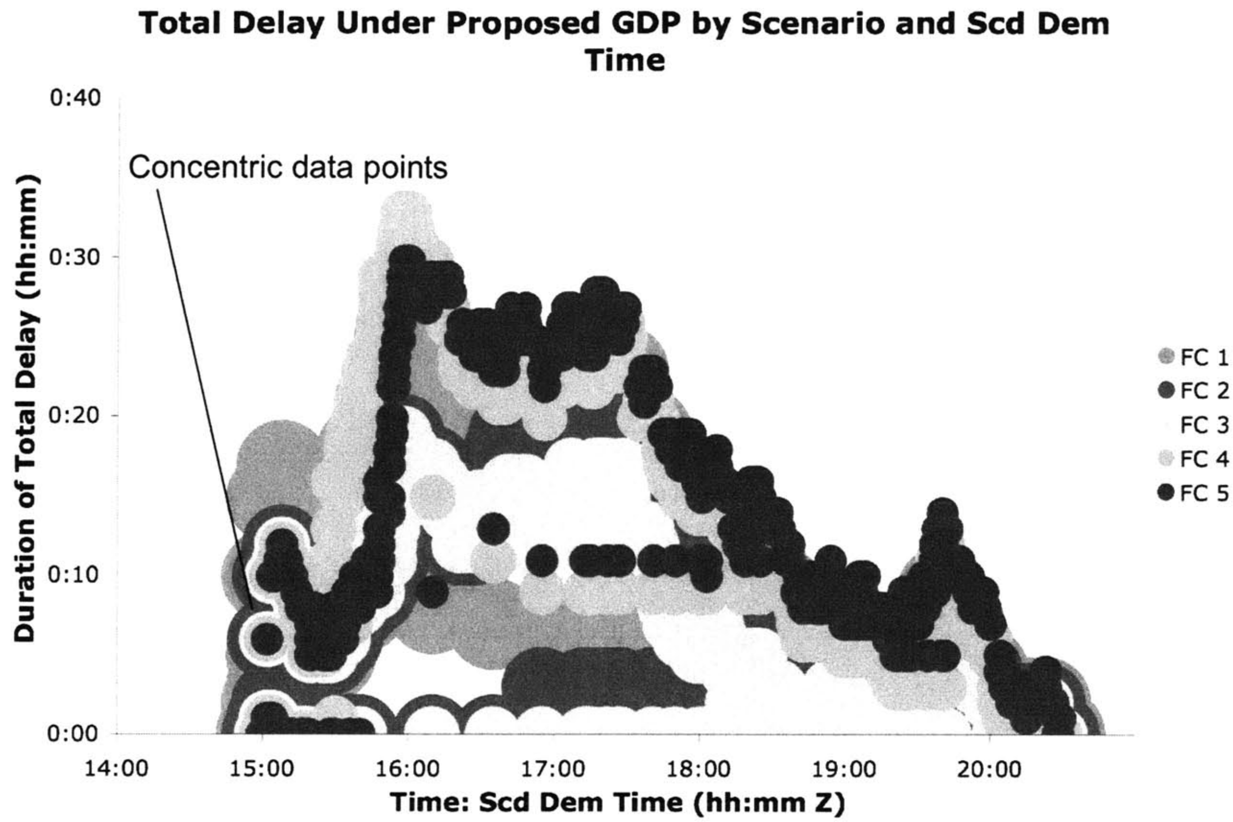

Figure 3-22: Total delays by flight and likelihood (by scheduled demand time)

Section 3.2.5: Slot Utilization

In addition to flight delays, the utilization of available arrival slots provides the traffic manager with key information about the strength of a proposed program. Available slots are determined by the capacity profiles and utilization tells the traffic manager how many of these slots would be used under the proposed program. Figure 3-23 is a sample table of the available slots by each capacity profile, including the base and proposed GDP[29,30]. In Figure 3-24, the utilization rates for each profile and time period have been calculated. In this example, the utilization rates have been shaded to show that, although the proposed program would achieve high utilization for FC 1, other potential outcomes result in an imbalance of both very low (< 80%) and very high utilization (= 100%). While low utilizations may indicate a wasted capacity, high utilization rates indicate a potential for significant airborne delay as there is no additional spare capacity if demand or capacity fluctuate slightly.

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[29] For slots per time period, please see Figure 4-4 in §4.2.2

[30] Note that this Excel model is a time-based simulation and breaks slots into one-minute increments; in this regard, the algorithms of FSM are approximated by the model – for further discussion, please see §4.2.3.

Arrival Slots by Time

	Capacity Profile						
Time	Base	GDP	FC 1	FC 2	FC 3	FC 4	FC 5
...							
15:00	2	1	1	2	2	2	2
15:01	2	1	1	1	2	2	2
15:02	1	1	0	1	1	1	1
15:03	2	1	1	2	2	2	2
15:04	2	1	1	1	2	2	2
15:05	1	1	0	1	1	1	1
15:06	2	1	1	2	2	2	2
15:07	2	1	1	1	2	2	2
15:08	1	1	0	1	1	1	1
15:09	2	1	1	2	2	2	2
15:10	2	1	1	1	2	2	2
15:11	1	1	0	1	1	1	1
15:12	2	1	1	2	2	2	2
15:13	2	1	1	1	2	2	2
15:14	1	1	0	1	1	1	1
...							

Figure 3-23: Available slots (in arrivals per minute) for different capacity profiles

Figure 3-23 (left):

Time is expressed in hh:mm Z
Arrival slots are expressed as aircraft
"Base" is the nominal airport arrival capacity
"GDP" is the arrival capacity based upon the PAARs

Figure 3-24 (below):

Time is expressed in hh:mm Z
Utilization is defined for each time period as the number of arrivals divided by the total arrival capacity.

Arrival Slot Utilization By Period

		Capacity Profile				
Time	Exp	FC 1	FC 2	FC 3	FC 4	FC 5
15:00	69%	90%	70%	56%	56%	56%
15:15	77%	100%	75%	60%	60%	60%
15:30	94%	100%	100%	80%	100%	80%
15:45	95%	100%	100%	80%	100%	80%
16:00	96%	100%	100%	80%	100%	100%
16:15	96%	100%	100%	80%	100%	100%
16:30	96%	100%	100%	80%	100%	100%
16:45	100%	100%	100%	100%	100%	100%
17:00	100%	100%	100%	100%	100%	100%
17:15	100%	100%	100%	100%	100%	100%
17:30	100%	100%	100%	100%	100%	100%
17:45	100%	100%	100%	100%	100%	100%
18:00	100%	100%	100%	100%	100%	100%
18:15	100%	100%	100%	100%	100%	100%
18:30	98%	100%	100%	84%	100%	100%
18:45	98%	100%	96%	92%	100%	100%
19:00	100%	100%	100%	100%	100%	100%

Figure 3-24: Utilization of available slots per time period and capacity profile

Section 3.3: Additional Metrics and Capabilities to Improve the GDP Decision-Making Process

Although the incorporation of uncertainty into the metrics used to evaluate a ground delay program improves the quality of information given to traffic managers, further improvements can be achieved by widening the scope of information considered in the appraisal of a proposed GDP. In this section, various enhancements are considered: adding new information, increasing the capabilities of the TM to assign delay, and an initial incorporation of dynamic elements into the decision process. These improvements are discussed in a similar order as §3.2, beginning with ways of classifying overall flight arrival demand.

Section 3.3.1: Categories of Arrival Demand

As has been discussed previously, understanding arrival demand is an important component of managing and planning a ground delay program. Although the need for a GDP is triggered by the overall arrival demand of aircraft, a program can only control those flights that have not yet departed. In considering whether of not to implement a GDP, a traffic manager will want to know not only the total arrival demand and how many flights are still on the ground, but also how these quantities are likely to change over time. FSM currently categorizes demand by flight status – on the ground, controlled (on the ground), or airborne – but does not include other relevant information that could assist in the evaluation of arrival demand.

The first illustration shown, Figure 3-25, is a chart that displays the arrival demand by time period for each capacity profile, similar to Figure 3-3. In this revised chart, however, demand is further divided by data source, differentiating between those flights that are airborne (Active), on the ground but with a filed flight plan (Planned), or taken from OAG data (Scheduled)[31]. If the traffic manager has any experience or other knowledge concerning the accuracy of each data source and how likely demand is to shift, he can use this display to help decide whether to include a buffer in the capacity forecasts.

Figures 3-26 and 3-27 are similar, except demand has been further broken down by departure time. Although this division is similar to that currently shown in FSM to illustrate how much of the anticipated demand could be controlled, the addition of departure time illustrates how much demand will no longer be controllable if the decision to implement the GDP is postponed. For example, in Figure 3-26 (no GDP), there are 20 flights due to arrive at the airport between 15:00 Z and 15:15 Z, six of which are scheduled to depart in the next 30 minutes (by 13:30 Z) and another five in the following half hour. By examining when flights are likely to depart, the traffic manager can see that, if no action is taken within a half hour (or less), airborne delays will become unavoidable, as flights will have departed; if no action is taken within an hour, the airborne delays will be significant. In Figure 3-27, the number of arrivals for the same time period has been decreased to 14, corresponding to the proposed GDP. However, in this example, not one of the flights with imminent departures was assigned ground delay. Therefore, even by enacting the proposed ground delay program, a revision, or update to the program, would be required within a half hour to prevent airborne delays.

[31] Although fluctuations in demand are outside the scope of this thesis, forecasted popups could also be included in this type of demand display

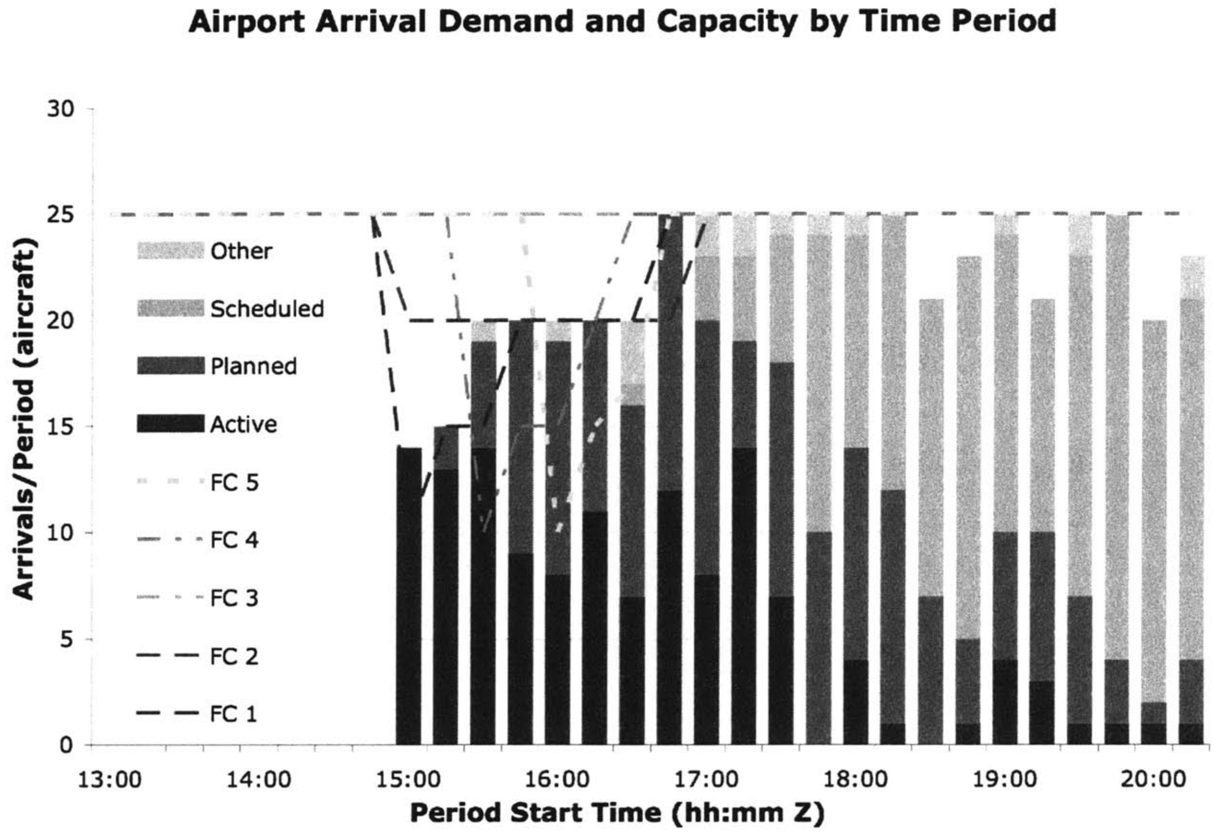


Figure 3-25: Arrival capacity and demand (by data source) profiles by time period

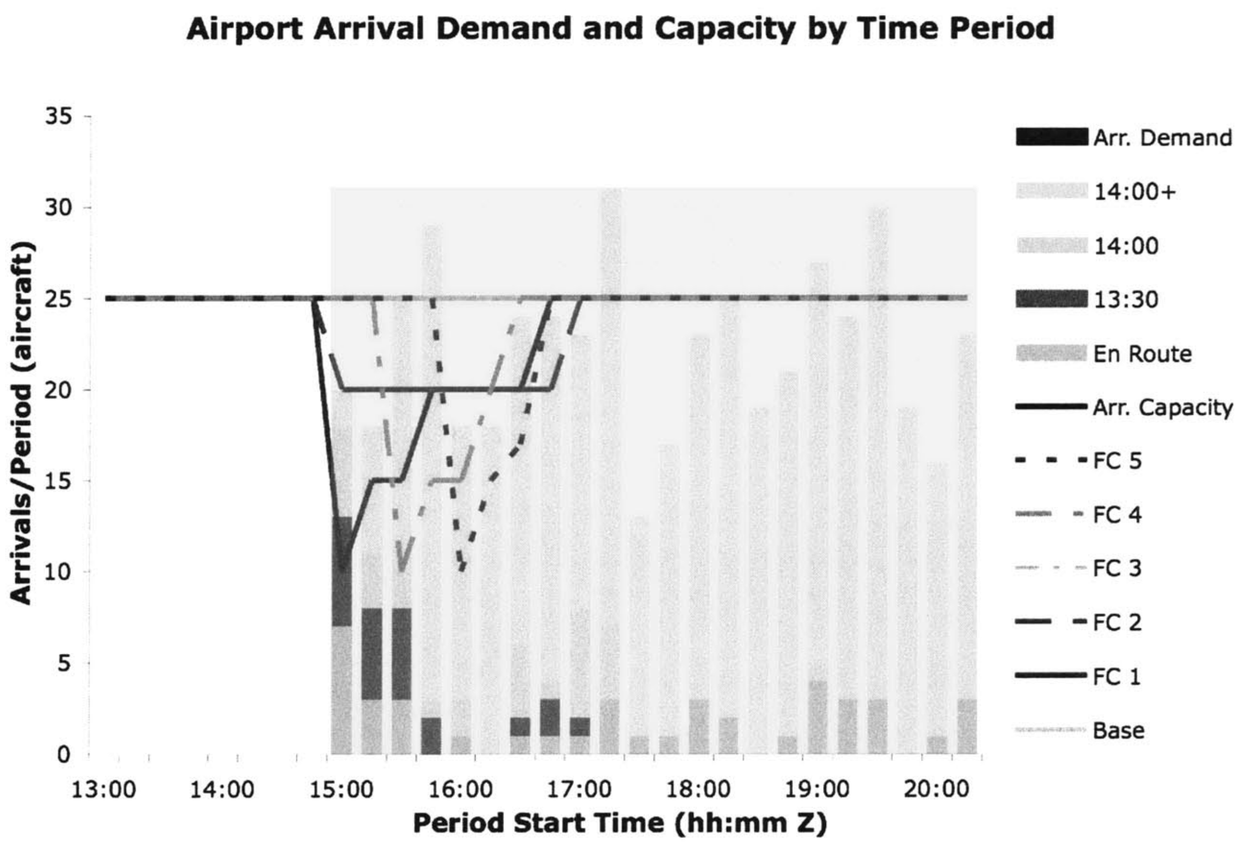


Figure 3-26: Arrival capacity and demand (by departure time) profiles by time period without a GDP

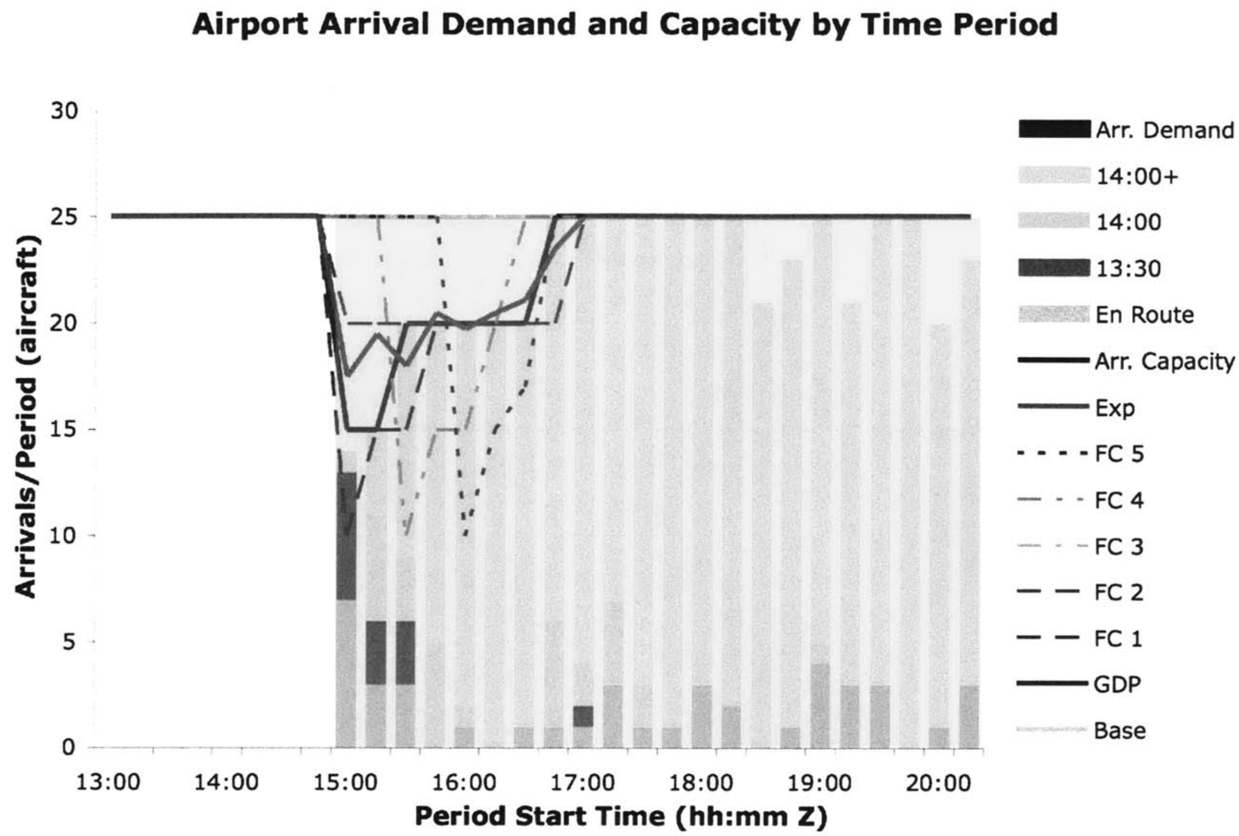


Figure 3-27: Arrival capacity and demand (by departure time) profiles for a GDP of reduced capacity

The importance of timing to GDP decision-making cannot be understated. As discussed in §2.3, while information improves and controllability declines with time, both are required for a successful ground delay program. The information contained in Figures 3-25 and 3-26 shows the traffic manager for how long their power to control flights will last, an important part of this tradeoff, leading to more informed decisions about the design and implementation of a GDP. Questions that can be addressed with the help of these figures include:

1. What data sources are currently used to forecast future demand?
2. How does the ability of the GDP to control demand decrease with time?
3. Assuming that this proposed program is implemented, by when would a revision be able to prevent further airborne delay?

Figures 3-25 and 3-26 are limited, however, by a lack of definition about exactly when decisions must be made and the penalty for waiting, questions that will be addressed in following sections.

Section 3.3.2: Comparing Air and Ground Delay

Although considering probabilistic arrival capacity forecasts when planning a GDP yields a great deal of information about the amount of air delays that may occur, the traffic manager still must compare these delays with those on the ground. The very purpose of a GDP – to exchange air delay for ground delay – reveals the underlying nature of these costs. Ground delay is typically considered much more desirable than air delay because of the increased safety and lower economic expenditures associated with taking a delay on the ground. In this vein, in addition to specific delays, the tool can also display a generalized cost for a proposed ground delay program.

The tool allows the user to specify a cost function for each type of delay. For the example GDP used in this thesis, the sample functions used to extrapolate delay costs for individual flights are shown in Figure 3-28[32]. As shown, air delay is assumed to have a standard cost twice that of ground delay and, after a period of time (in this example, 1 hour), a dramatic increase in cost due to the likelihood of flight diversions.

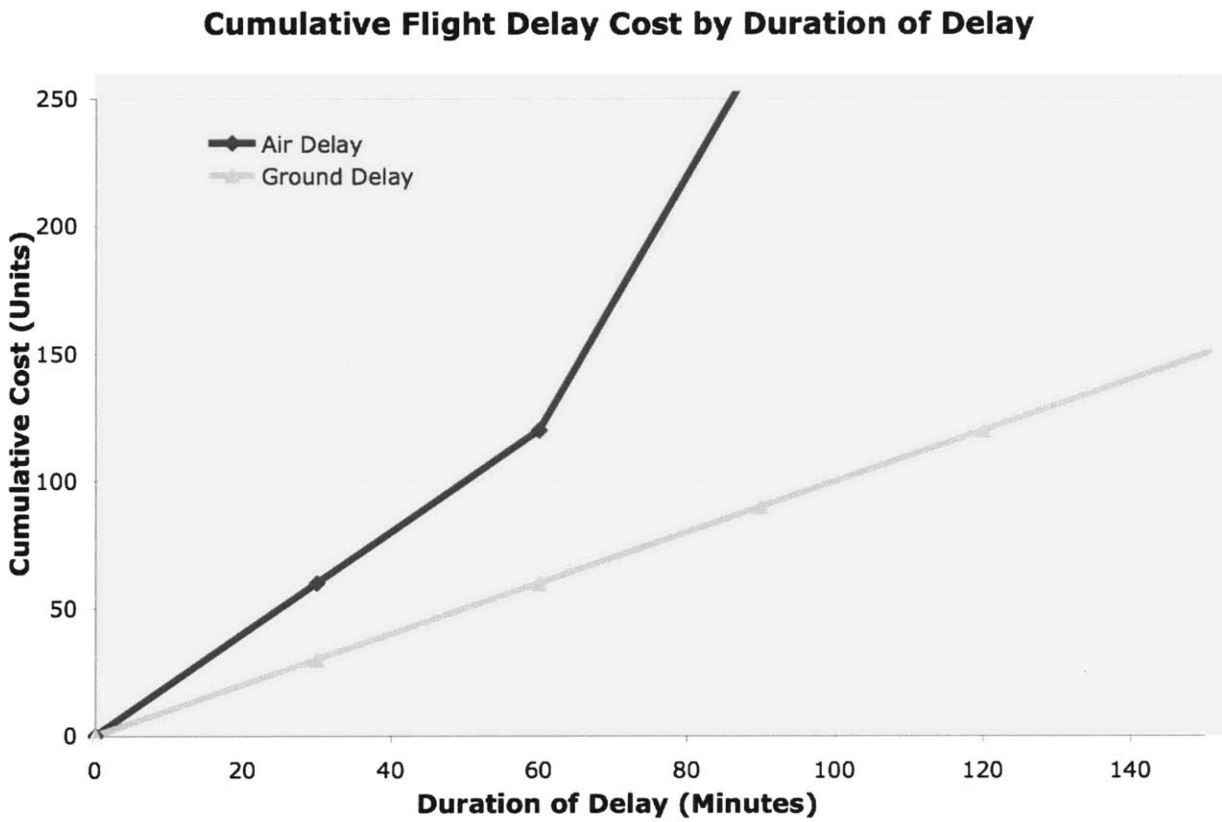


Figure 3-28: Cost functions for air and ground delay

The use of cost functions allows the integration of air and ground delays that were previously discussed separately in §3.2. For example, Figure 3-29 illustrates the calculation of total delay costs by flight using the cost functions illustrated in Figure 3-28. In Figure 3-29, the delay costs shown are for all of the different possible capacity profiles; instead of comparing the assigned ground and forecasted delay across the different outcomes, the traffic manager now needs only to compare the total costs. From a broader perspective, the sum of all delay costs across all flights (Figure 3-30) could be seen as a total score for a proposed ground delay program, incorporating both air and ground delay and the many possible outcomes[33].

[32] Figure 3-28 is actually an interpretation of the cost functions that are used in the model. For a more detailed discussion, please refer to §4.2.5.

[33] The author feels, however, that proposed ground delay programs are far too sophisticated to be reduced to a single value; for example, expected cost does not consider how delay is distributed or accumulated over time.

Flight Ground and Airborne Delay Costs by Outcome							
	Ground			Airborne Delay Cost			
Flight ID	Delay Cost	Exp	FC 1	FC 2	FC 3	FC 4	FC 5
53A1186	0	0.0	0	0	0	0	0
53A111	0	0.8	2	0	0	0	0
10A305	0	2.8	4	2	2	2	2
47A126	6	3.2	8	0	0	0	0
53A529	0	1.6	4	0	0	0	0
01A829	0	3.0	6	2	0	0	0
01A311	0	5.8	10	4	2	2	2
10A321	10	4.0	10	0	0	0	0
01A548	10	4.0	10	0	0	0	0
27A310	0	2.4	6	0	0	0	0
50A6808	11	4.0	10	0	0	0	0
53A379	12	4.0	10	0	0	0	0
10A749	0	3.2	8	0	0	0	0
20A1746	0	4.0	10	0	0	0	0
28A963	11	4.0	10	0	0	0	0
20A1175	0	4.0	10	0	0	0	0
01A643	0	4.0	10	0	0	0	0
10A803	10	4.0	10	0	0	0	0
53A945	0	4.0	10	0	0	0	0
48A46	9	4.0	10	0	0	0	0
...							

Figure 3-29: Assignment of delay cost by flight

Total Delay Cost Summary Statistics						
				Capacity Profile		
	Exp	FC 1	FC 2	FC 3	FC 4	FC 5
Min	0.0	0.0	0.0	0.0	0.0	0.0
Mean	13.5	16.1	9.4	7.2	21.3	21.7
Max	28.6	34.0	23.0	19.0	48.0	43.0
Spread	28.6	34.0	23.0	19.0	48.0	43.0
StDev	8.7	10.3	7.3	6.0	13.0	12.3
Coeff Var.	1.55	1.56	1.29	1.20	1.65	1.77
Total	6,596	7,822	4,592	3,490	10,386	10,558

Total Flights	487	487	487	487	487	487
+/- 1 StDev	255	275	255	250	346	259
+/- 2 StDev	487	487	487	487	483	487

All costs are expressed in units of cost
Min, Mean, Max are the minimum, expected value, and maximum of flight delays
Spread is Max - Min
The coefficient of variation is defined as Mean/StDev and is unitless
+/- StDev refers to the number of flights within a standard deviation of the mean
Flight counts are expressed in number of aircraft

Figure 3-30: Summary of delay cost distributions by flight and scenario

Figure 3-30 also extends into equity considerations – the distribution of delay costs across flights. As before, such distributions can be partially summarized by the mean values and standard deviations. In the provided figure, both FC 4 and FC 5 result in a similar, significant delay cost, but the distribution of cost for FC 5 could be interpreted as being less equitable because only 259 of 487 aircraft receive a delay cost within one standard deviation of the mean, as compared to 346 for FC 4. These distributions can be compared across different proposed programs to understand how each is likely to distribute delays among aircraft.

The next illustration, Figure 3-31, is a histogram of the cost of delays as attributed across all flights. Instead of a single metric, the histogram shows how each forecasted capacity profile distributes the total cost of delay. Of course, as delays vary over the course of a program, summary statistics can also be computed for smaller periods of time (e.g. Figure 3-20) or delay cost can be plotted by time (similar to Figure 3-8). Further examples, including those that combine costing with other techniques, can be found later sections.

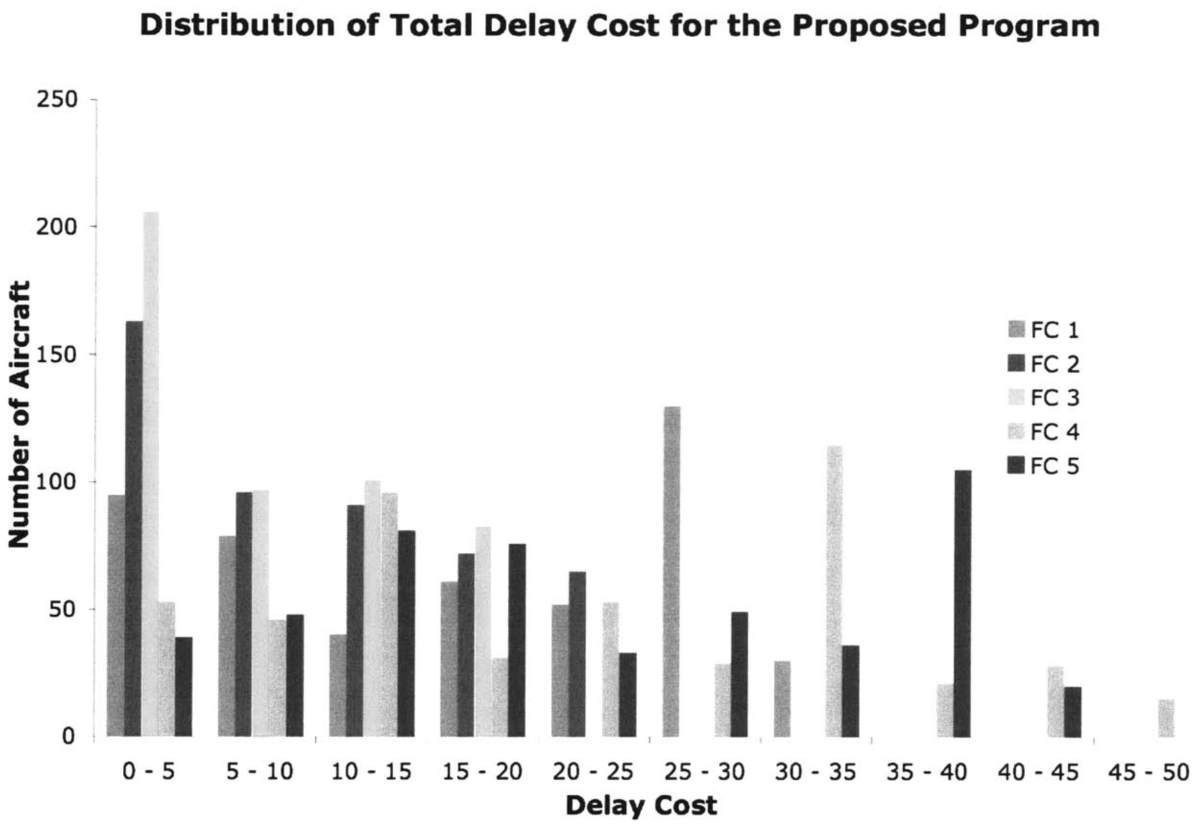


Figure 3-31: Histogram of total delay cost distributions by flight and scenario

On the surface, the use of functions to generalize overall delay costs greatly simplifies the second key tradeoff for the traffic manager, whereby ground delays are compared to the likelihood of air delays. A key element of this decision remains, however: the timing of when delays occur. Figure 3-32 illustrates the accumulation of delay cost over time. Note that this chart is similar to Figure 3-17, except that the minutes of air and ground delay have been combined and replaced with a generalized cost, which facilitates the comparison of one possible outcome to another (or one proposed program to another). For example, while Figures 3-32 and

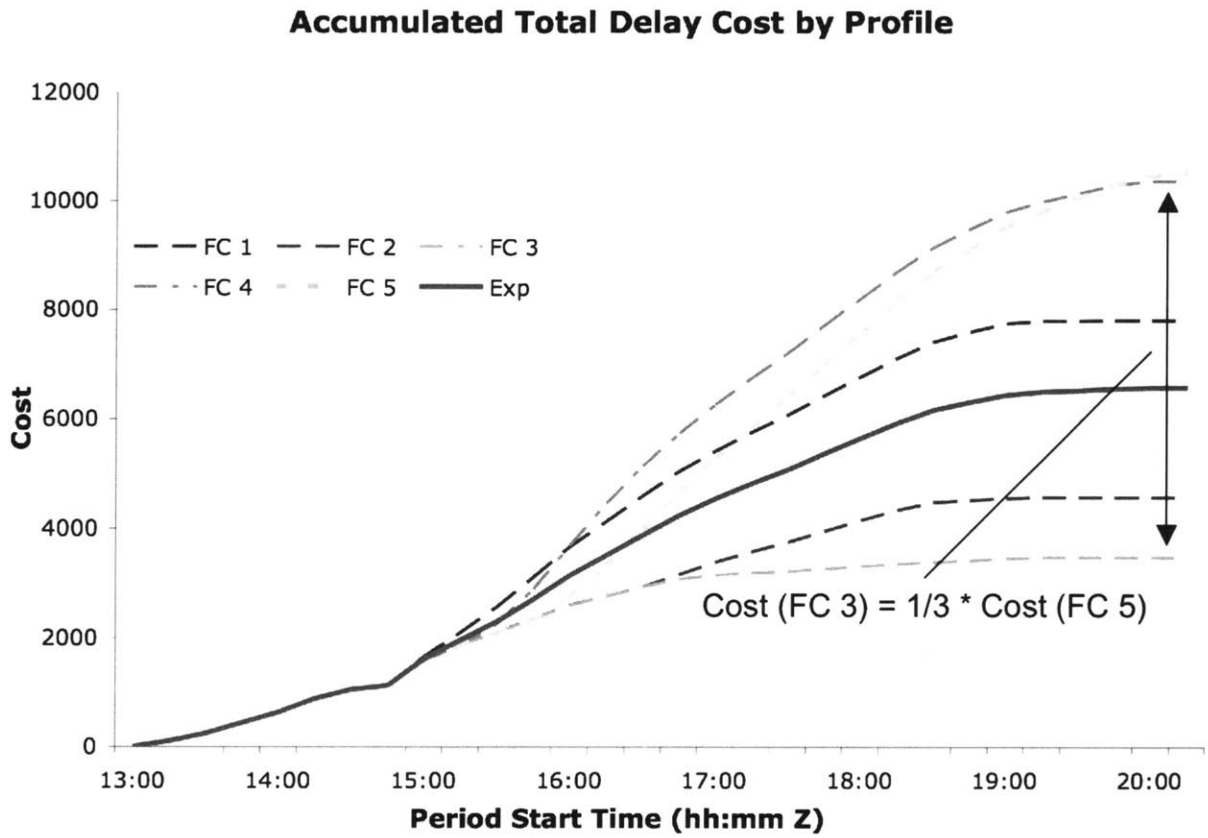


Figure 3-32: Accumulation of total delay cost over time

3-17 both show a similar pattern in the possible outcomes, with FC 4 and FC 5 being the least preferable, Figure 3-32 shows that the range in magnitude among the values of the different possible outcomes is nearly three, as opposed to two.

The use of generalized cost functions helps clarify many of the questions mentioned in §3.2.4. For brevity, they will not be reproduced, however, some of the most important include:

1. What is the expected cost of delay of this proposed program?
2. How are delay costs distributed among aircraft?
3. Do any aircraft bear an unusually large cost of delay (often due to possible diversion)?
4. How are delay costs accumulated over time?

Despite the benefits of combining air and ground delay into a single metric, from the perspective of GDP decision-making, the difficulties in comparing air and ground delay have not been avoided. Further study, beyond the scope of this thesis, is required to identify the appropriate functions for airborne and ground delay. At this point, the key observation is that it is possible to use a customizable cost function to simplify the evaluation of a program.

Section 3.3.3: Delay Avoidance

The incorporation of uncertain arrival capacities has led to the creation of the expected cost of delay as a metric to compare proposed ground delay programs. There is, however, a further twist to the forecast of arrival capacities, which leads to additional information that can be used to guide decisions: dynamic forecasts. As discussed in §2.3.3, a traffic manager may have information about future forecasts, in addition to the current likelihoods of the arrival capacity profiles. Even if all that is known is that an updated arrival capacity forecast will be received by a certain time, a traffic manager should consider the costs and potential benefits of waiting for that forecast.

Current consideration of the dynamic nature of GDPs is limited to a metric called unrecoverable delay, which shows the future accumulation of ground delay over time, effectively illustrating how much of the assigned delay could be prevented if a program is cancelled. The one-sided nature of unrecoverable delay, results in a metric of limited usefulness. The revisions to FSM as proposed in this thesis might create an opportunity to expand the notion of when action could be taken to prevent both ground and air delays by considering a new metric called unavoidable delay.

Unavoidable airborne delay, $AAv_c(t)$, is defined as the total amount of airborne delay that is expected to be experienced by all flights that are airborne as of time t[34]:

$$AAv_c(t) = \sum_{f \mid \delta_f < t} \left(\alpha_{f,c} - \omega_f\right) \qquad (f3.1)$$

where

δ_f is the departure time of flight f

$\alpha_{f,c}$ is the arrival time of flight f under capacity profile c

ω_f is the demand time of flight f

Effectively, unavoidable delay measures delay not as it occurs, but at the time at which a traffic manager could, instead, act to delay flights on the ground. Once a flight departs, it can no longer be held on the ground and all delay will be taken in the air; thus, unavoidable delay attributes all expected future airborne delays of a single flight to the departure time of that flight[35].

Figure 3-33 shows the accumulation of unavoidable delay if a GDP is not proposed at the current time. At 14:45 Z, unavoidable delay sharply increases due to a rise in the number of departures, especially for forecasts FC 1 and FC 4. The figure shows that if a GDP is filed by 14:45 Z, this spike in future airborne delay can, instead, be taken on the ground. Figure 3-34 illustrates the accumulation of unavoidable airborne delay with the current proposed GDP. In comparison, implementing a GDP at the current time reduces the impetus to act by 14:45; it more than halves the total expected airborne delay that could be avoided by 14:45 Z (from more than 1300 aircraft minutes to less than 500) and smoothes the ensuing spike in unavoidable delay, especially for FC 1.

Ground delay can also be avoided. Unlike airborne delay, however, ground delay for a given flight can be avoided at any time if that flight is allowed to depart. However, flights can rarely depart immediately if GDPs are suddenly cancelled, requiring some additional time to board, depart from the gate, taxi, etc. Therefore, unavoidable ground delay is the amount of

[34] An alternate derivation is shown in §4.5.2

[35] Future air delays can still be reduced by delaying *other* flights

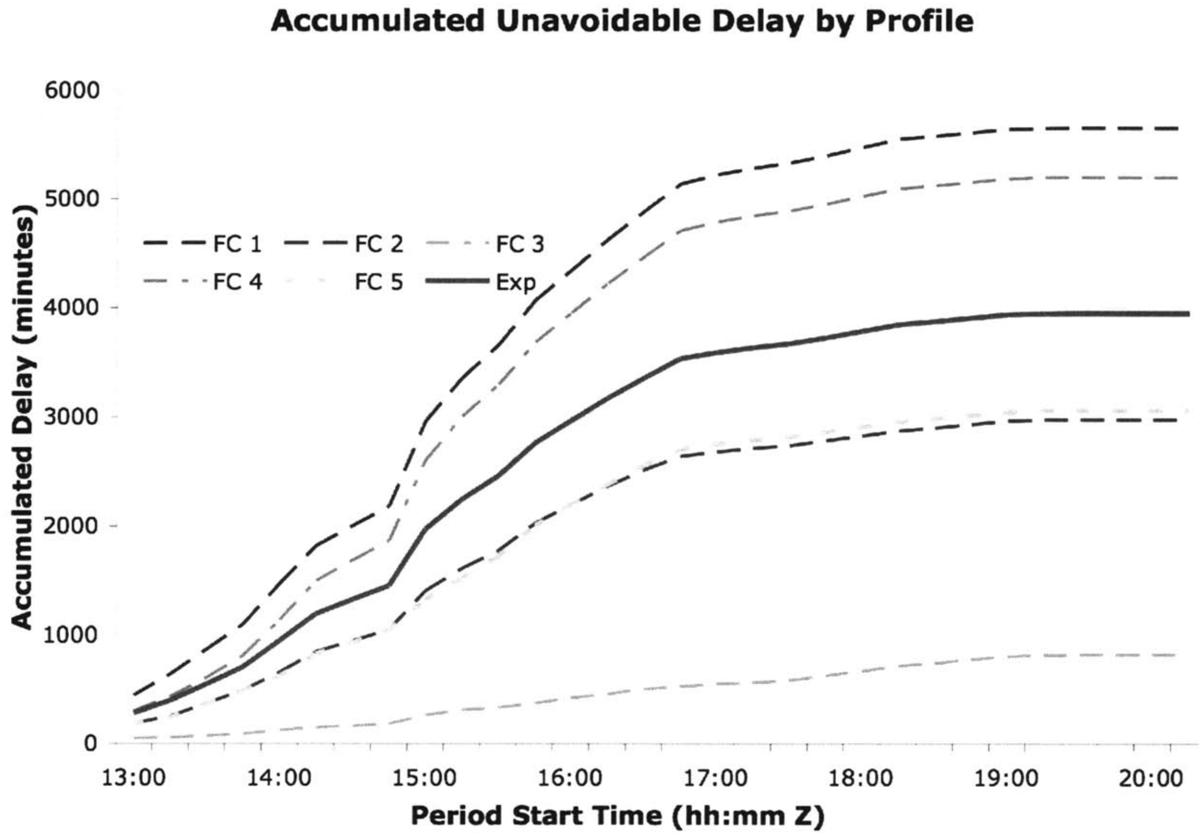


Figure 3-33: Cumulative unavoidable airborne delay if no GDP is implemented

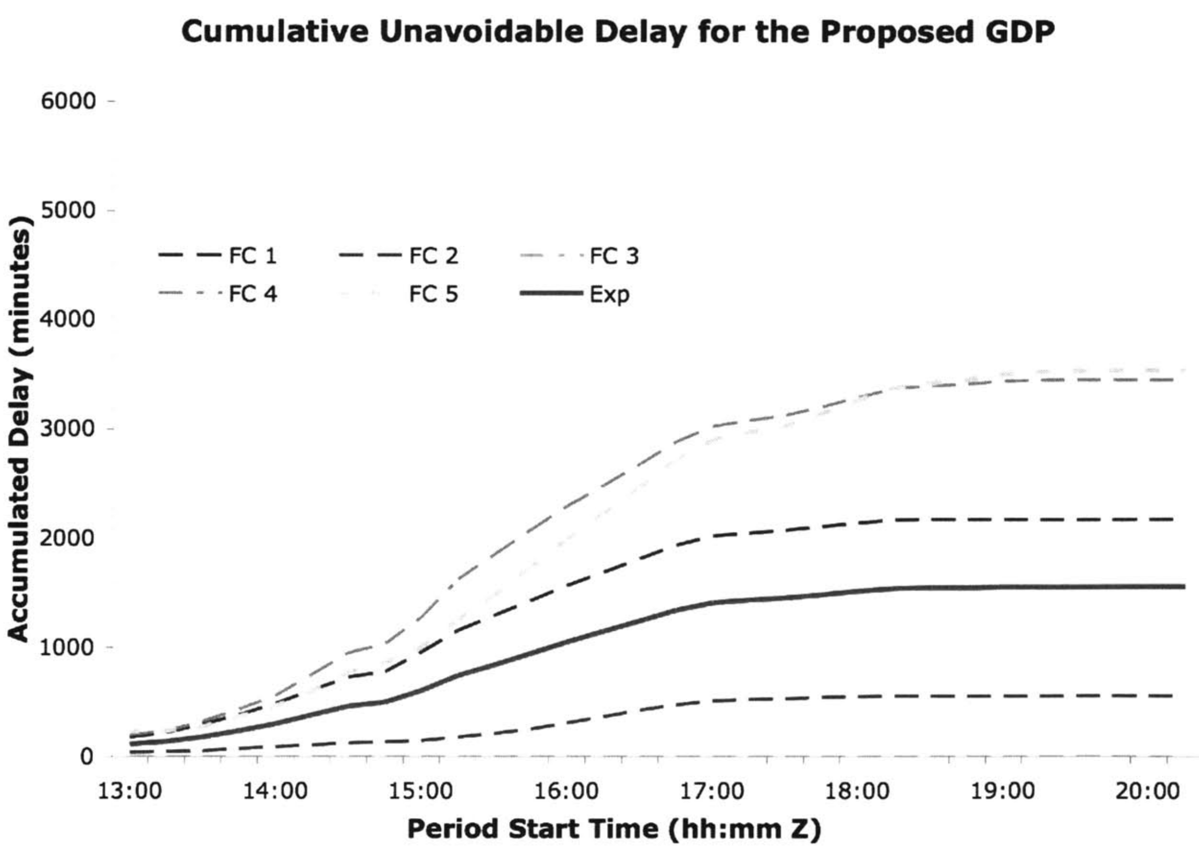


Figure 3-34: Cumulative unavoidable airborne delay if the proposed GDP is implemented

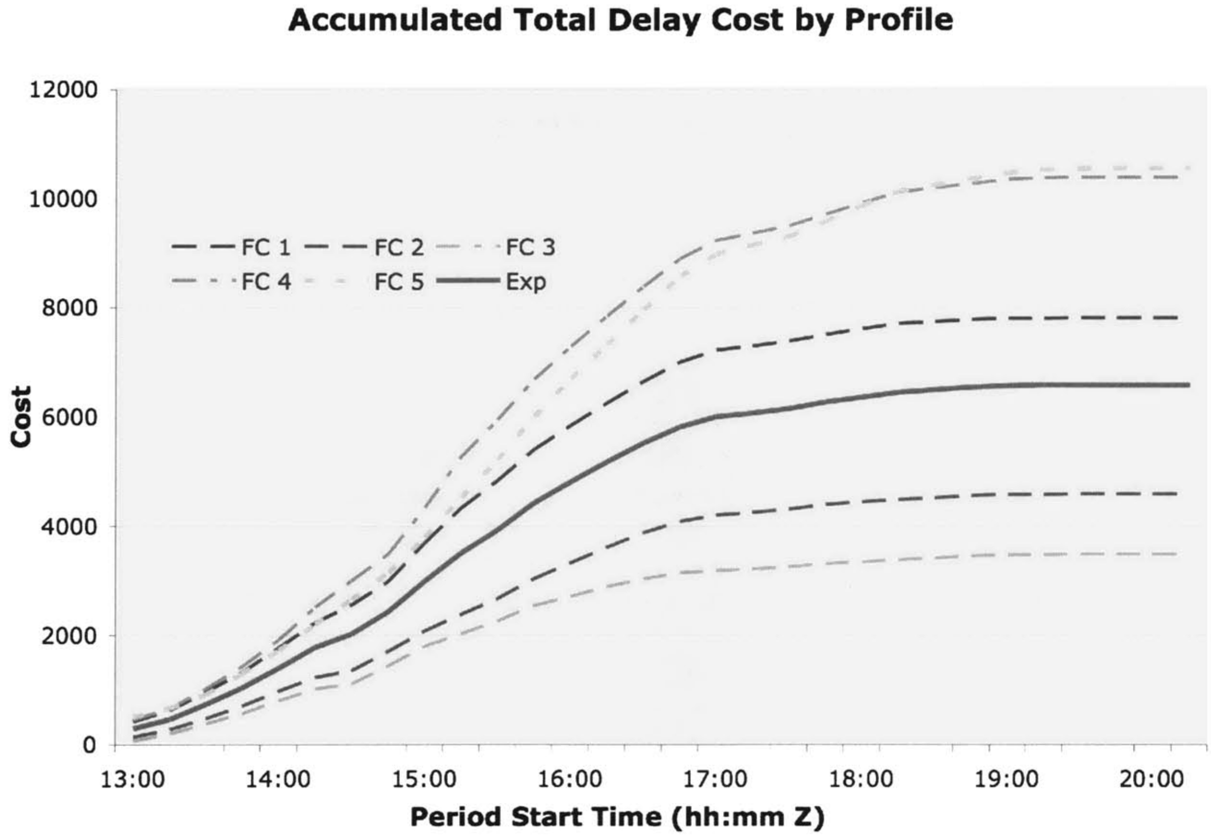


Figure 3-35: Total unavoidable delay cost for the proposed ground delay program

ground delay that has already been incurred plus this additional time, which is also referred to as "preparation time." Preparation time is often (though, not always) on the order of only a few minutes and, for demonstration purposes, is assumed here to be 10 minutes per flight. Please see §4.5.2 for more information.

Unavoidable ground and airborne delay can also be compared using delay cost. Previously, §3.3.2 detailed how the cost of delay can be computed for each flight and then summed across all flights. In the same manner, unavoidable delay costs are calculated; the chart in Figure 3-35 shows the accumulation of unavoidable delay cost over time for the proposed program.

Section 3.3.4: Equity Considerations

One of the more difficult aspects of a ground delay program to measure is equity, the distribution of delay among flights. As airborne delays are inherently uneven in distribution over time, the ground delays assigned to flights are also expected to vary by time, compromising the use of simple statistical summary functions for evaluating the distribution. As discussed previously (§3.2.2), a traffic manager can use time and delay plots to visually inspect a program for flights assigned unusually large values for delay. In this section, two alternative measures, designed to adjust for temporal distortions are proposed. The first adjusts delay by a moving average and the second borrows from economics literature to compute a delay share.

Delay Distributions

One way to improve comparisons of equity would be to examine the delays assigned to flights traveling at similar times. Although delays will vary over time, this variation can be partially accounted for by comparing a flight to the average of other flights with similar demand times. Figure 3-36 illustrates the delay for each flight less the average delay of flights with scheduled demand times immediately prior to and after the given flight, or a simple moving average. In this example, four flights are used for the average (two before and two after) and the expected total delay is shown. The distance between a given flight and the x-axis, centered at a zero delay value, represents the difference between the delay received by a flight and the moving average.

From this single graph, two qualities of the ground delay program become clear. First, expected delays are most disparate at the beginning of a program when many flights are already airborne or otherwise exempt. Second, large negative spikes represent other exempt flights[36] and cause imbalances of delays later during the program. This plot can also be used to compare different proposed programs to see which results in the least variability of delay among flights.

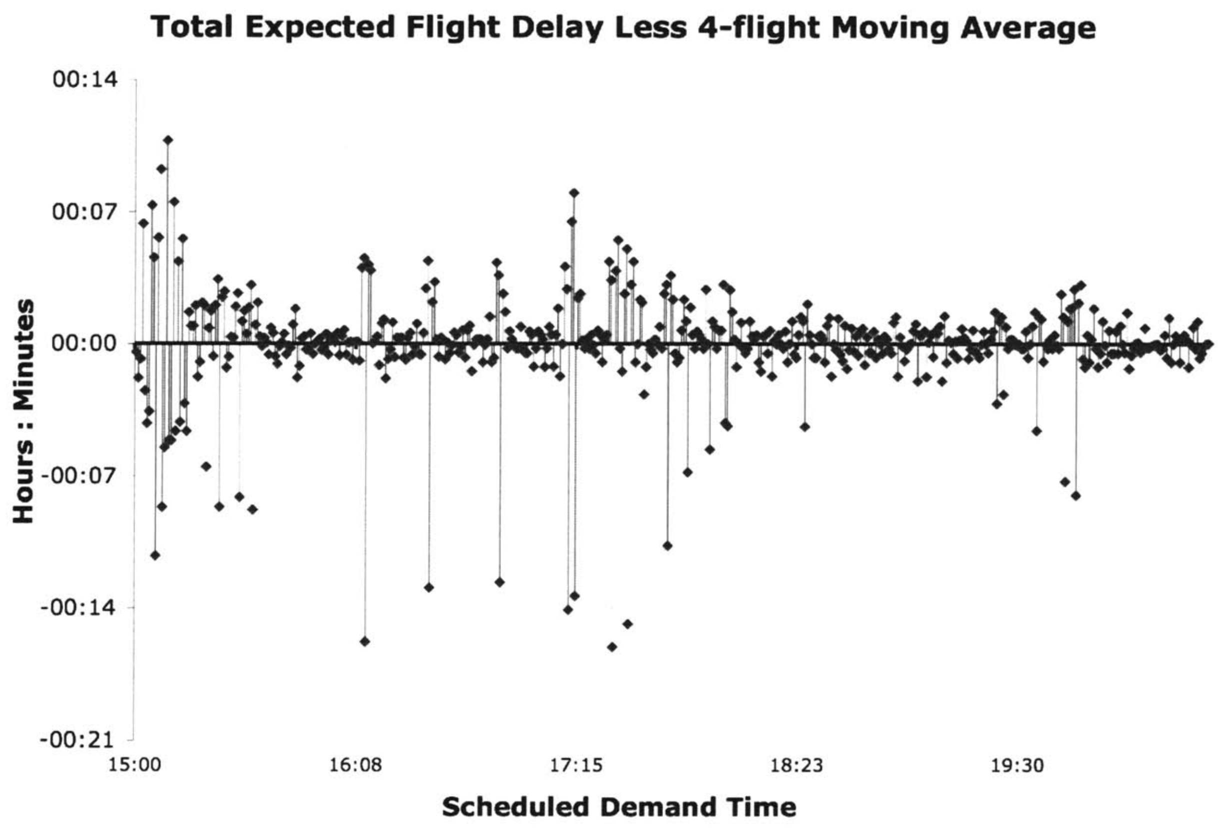


Figure 3-36: Expected flight delays compared to the 4-flight moving average, by scheduled demand time

Distribution Ratios

The delay share of a flight ($DS_{f|c}$) is the amount of delay that a single flight is expected to receive in proportion to the sum of expected delays across all flights for a given capacity profile.

---

[36] For the GDP example used in this discussion, only international airports are excluded

Sample delay shares are expressed as percentages between 0% and 100% and are shown in Figure 3-37. Although this share indicates how much of the total delay is attributed to a single flight, it does not summarize how delay is distributed over all flights. This problem is frequently encountered in economics literature, however, as the market share of individual firms in a market is used to understand the level of competition and monopolistic tendencies in that market.

One measure that is used to characterize the behavior of an entire market from individual market shares is the Herfindahl-Hirschman Index (HHI_c). The HHI is the sum of the squared market share percentages across the market and takes a value between 0, indicating a marketplace with an infinite number of equal competitors, and 10,000, indicating a single firm. In this same manner, the HHI can also be used for flight delays, replacing market share with delay share. However, the application of HHI is sensitive to the size of the marketplace, a factor that the traffic manager does not control. For this reason, the tool calculates an adjusted version of the HHI, herein called H3[37], which is the ratio of the HHI for a given program and the ideal HHI if delay was distributed evenly among participants.

$$DS_{f|c} = \frac{Delay_{f|c}}{\sum_{f \in \Im} Delay_{f|c}} \qquad (f3.2)$$

$$HHI_c = \sum_{f \in \Im} (100 \times DS_{f|c})^2 \qquad (f3.3)$$

$$H3_c = \frac{HHI_c \times (\sum_{f \in \Im} 1)^2}{100^2} \qquad (f3.4)$$

where
f is a flight, $f \in \Im$
c is a capacity profile, $c \in \Omega$

Flight Delay Shares		
Flight ID	Ground Delay	Delay Share
53A1186	0:00	0.00%
53A111	0:00	0.00%
10A305	0:00	0.00%
47A126	0:06	0.17%
53A529	0:00	0.00%
01A829	0:00	0.00%
01A311	0:00	0.00%
10A321	0:10	0.29%
01A548	0:10	0.29%
27A310	0:00	0.00%
50A6808	0:11	0.32%
53A379	0:12	0.34%
10A749	0:00	0.00%
20A1746	0:00	0.00%
28A963	0:11	0.32%
20A1175	0:00	0.00%
01A643	0:00	0.00%
10A803	0:10	0.29%
53A945	0:00	0.00%
48A46	0:09	0.26%
...		

Delay is expressed in hh:mm

Figure 3-37: Sample flight delay shares

Figures 3-38 and 3-39 show $H3_c$ and the overall expected value of the H3 score for both the total delay and the total delay cost shares for the proposed program. As shown, the indices for the total delay and total cost measures are similar and relatively low for the proposed program. For the different forecast outcomes, FC2 and FC3 have $H3_c$ ratios that are larger than those of other programs, which indicate that the proposed program distributes delay less efficiently for these possible outcomes. Understanding the further significance of the H3 score requires additional study to calibrate the metric. For example, $H3_c$ could be calculated for historical programs whose outcomes are already known to determine what ranges of scores are to be considered "good" or "bad."

[37] The "Hanowsky Ratio of the Herfindahl-Hirschman Index"

Total Delay Summary Statistics						
	Capacity Profile					
	Exp	FC 1	FC 2	FC 3	FC 4	FC 5
Min	0:00	0:00	0:00	0:00	0:00	0:00
Mean	0:10	0:11	0:08	0:07	0:14	0:14
Max	0:23	0:26	0:20	0:19	0:33	0:30
Spread	0:23	0:26	0:20	0:19	0:33	0:30
StDev	0:07	0:07	0:06	0:05	0:09	0:08
Coeff Var.	1.43	1.46	1.27	1.20	1.55	1.66
Total	84:01	94:14	67:19	58:08	115:36	117:02
Total Flights	487	487	487	487	487	487
+/- 1 StDev	265	261	261	248	302	286
+/- 2 StDev	487	487	487	487	482	487
H-H	31	30	33	35	29	28
Perf H-H	21	21	21	21	21	21
H3 Ratio	1.49	1.47	1.62	1.69	1.42	1.36

Figure 3-38: Summary statistics for total delay

Total Delay Cost Summary Statistics						
	Capacity Profile					
	Exp	FC 1	FC 2	FC 3	FC 4	FC 5
Min	0.0	0.0	0.0	0.0	0.0	0.0
Mean	13.5	16.1	9.4	7.2	21.3	21.7
Max	28.6	34.0	23.0	19.0	48.0	43.0
Spread	28.6	34.0	23.0	19.0	48.0	43.0
StDev	8.7	10.3	7.3	6.0	13.0	12.3
Coeff Var.	1.55	1.56	1.29	1.20	1.65	1.77
Total	6,596	7,822	4,592	3,490	10,386	10,558
Total Flights	487	487	487	487	487	487
+/- 1 StDev	255	275	255	250	346	259
+/- 2 StDev	487	487	487	487	483	487
H-H	29	29	33	35	28	27
Perf H-H	21	21	21	21	21	21
H3 Ratio	1.42	1.41	1.60	1.69	1.37	1.32

All costs are expressed in units of cost
All times are expressed as hh:mm
Min, Mean, Max are the minimum, expected value, and maximum of flight delays
Spread is Max - Min
The coefficient of variation is defined as Mean/StDev and is unitless
+/- StDev refers to the number of flights within a standard deviation of the mean
Flight counts are expressed in number of aircraft
"H-H", "Perf H-H", and "H3 Ratio" refer to the Herfindahl-Hirschman Index

Figure 3-39: Summary statistics for total delay cost

Section 3.4: A Two-Stage Arrival Capacity Model for FSM

This thesis focuses on the inclusion of considerations of uncertainty in the GDP decision process. As discussed in §2.3.3, however, current FSM metrics – and most enhancements proposed in this thesis – are static. When expected delays are calculated, they do not incorporate the dynamic nature of both information and the ground delay program, itself. Arrival demand and capacity forecasts will change over time, and the traffic manager has the power to revise a ground delay program to reflect this new information. To make the most-informed decisions about the design of a ground delay program, FSM should consider the GDP not in isolation but as it is viewed by the traffic manager: a dynamic response to a dynamic problem.

Some of the metrics previously discussed allude to the possibility of revising a GDP. For example, avoidance time (§3.3.3) indicates the time by when a program would need to be revised to avoid additional delays. It stops short, however, of actually detailing how the program would be revised. The final contribution of this thesis is to create two additional models that incorporate more dynamic elements of GDP planning to assist with the design of a ground delay program. The first dynamic capability is to allow the traffic manager to project decisions further out in time to see, given a current course of action, exactly what opportunities will be available at a future time. The second element is that the tool, itself, can anticipate future revisions of a program and reflect these updates in the delay and cost summaries presented to the traffic manager at the time of the initial decision.

Section 3.4.1: The Global Time Variable

Using the current flight information provided by ETMS and the different arrival capacity forecasts, it is possible to forecast the position and status of all flights (pre-departure, in ground hold, en route, in queue, or post-arrival) at any time during a proposed program. This functionality is captured in previous figures, for example, forecasted arrival and ground hold queue sizes by time (Figures 3-12 and 3-5). What these visual displays lack, however, is an indication of how changes to the GDP at future times would impact these forecasts.

Unlike FSM, the tool allows the user to control a global system time variable, which determines the instant at which the "location" of a flight – and its potential for the assignment of ground delay – are evaluated. Those flights that are *scheduled* to have departed by this time are exempted from ground delays. In this way, a traffic manager can create a hypothetical scenario to see how a proposed program might perform if the filing time was delayed. For example, Figure 3-17 shows the accumulated airborne arrival delays by profile over time for the proposed GDP. If the same GDP were to be filed with a 30-minute postponement, however, Figure 3-40 shows that the expected airborne delays increase by more than 400 minutes. By using the global time variable, the TM can explore the tradeoff between time and control power.

Furthermore, if the traffic manager has knowledge of how arrival forecasts are likely to change, the ability to set the system time can also be used in conjunction with revised forecasts to explore possible future decisions. The tool allows the user to propose a GDP, record the resulting controlled departure times, update the capacity scenario, and then revise the proposed program. Because of the design of the model, as long as the future capacity forecasts can be provided, the decision stages in the model can continue indefinitely. Although such forecasts are outside the scope of this thesis, it might be possible to envision a capacity scenario tree, in which an update to a given capacity scenario can take one of several forms, which are known a priori. The next section will discuss the special case of the scenario tree.

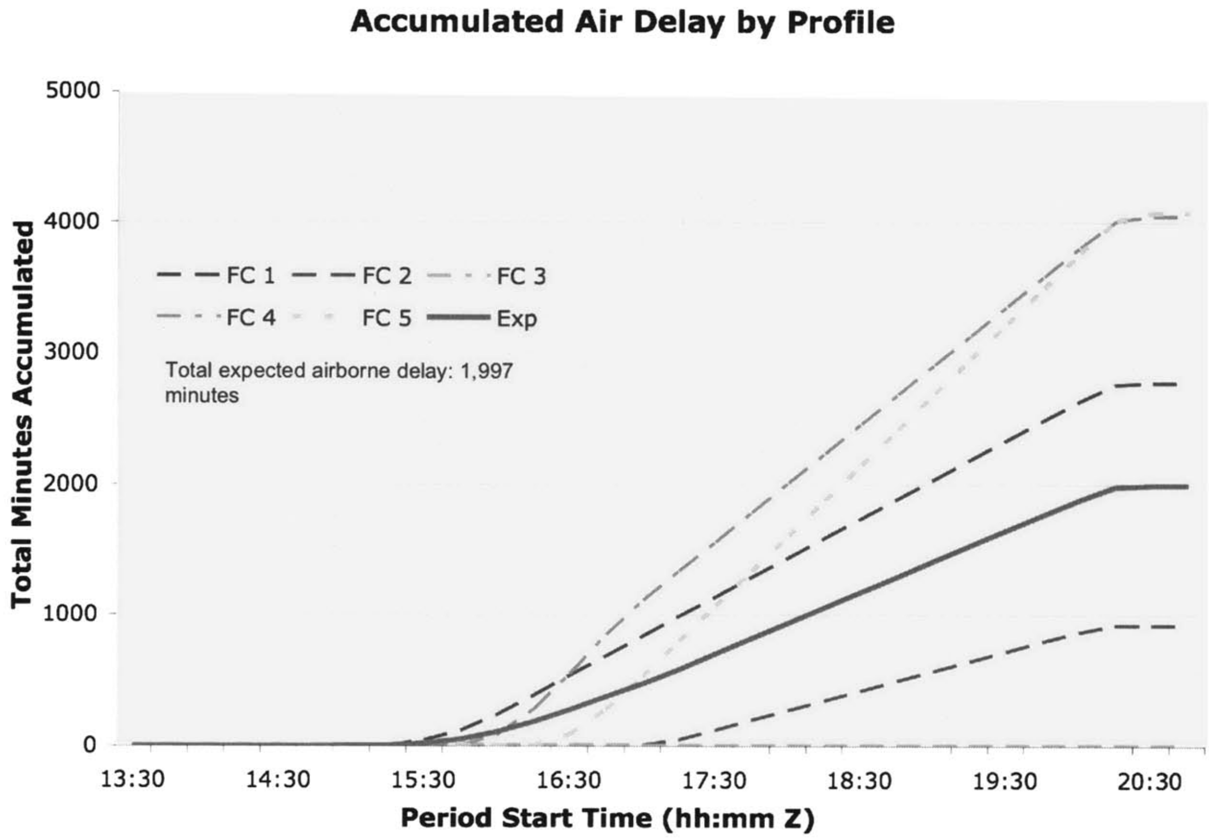


Figure 3-40: Accumulated airborne arrival delays by time with a 30 minute GDP postponement

Section 3.4.2: The Two-Stage Decision Model

For the simplest case, we can assume that, at an initial time (t_0), we are given a capacity scenario (Ω_0) and a proposed ground delay program. The traffic manager also expects that at future time (t_{pi}), the weather forecast will be updated to reflect the weather that will actually occur and that the TM will be able to revise the program accordingly. That is, the traffic manager is able to set a ground delay program at t_0 that will be optimally revised to reflect deterministic forecasts that become available at time t_{pi}, which is assumed to be far enough in the future that additional flights will have departed, but not so far that there will not be any flights left to control. At the very latest, t_{pi}[38] could be interpreted as the time at which the traffic manager could simply look outside to check the weather!

For a GDP proposed at t_0, the two-stage model considers one potential outcome for each capacity profile, whereby the PAARs of the proposed program will be changed at t_{pi} to reflect the AARs.[39] When the rates change, the two-stage model uses the tool to create a new GDP for each possible AAR and reassigns ground delays, using the revised departure times of the original GDP to determine which flights have yet to depart and are still eligible for control.

[38] t_{pi} is also called the "time of perfect information"

[39] The tool can apply the two-stage model under any circumstances in which the PAARs are deterministically defined by a given capacity scenario

Figure 3-41 illustrates the accumulation of total delay cost if the originally proposed ground delay program is revised at 15:15 Z. Each capacity profile is represented by a single curve, which indicates the accumulation of delay if that profile is the one actually realized. The delays are calculated by creating a new GDP at 15:15 Z for each of the profiles using the global time variable. As the actual forecast is assumed to be known with certainty at this time, the capacity rates of the profile are used for both the PAARs of the GDPs, and the actual arrival rates. In this manner, the two-stage model can be applied to either the original schedule of flights or to the proposed and demand times that result from an earlier GDP (please see Figure 4-10 in §4.6).

As compared to Figure 3-32, discussed in §3.3.2, Figure 3-41 shows that anticipating the revision substantially lowers the expected cost of the proposed program. It is not that the actual costs will be different – because, in situ, the proposed GDP would have been revised – just that the new cost estimate (at t_0) assumes that the traffic manager would correctly revise the program at a later time. When comparing costs across different proposed GDPs, anticipating revisions will not necessarily lead to the same cost reduction for each of the programs as the power to revise a GDP depends on how many flights are left to control. Correspondingly, assuming that GDPs can be revised allows for a more accurate comparisons; the best overall choice may be the initial "second best" solution: the optimal GDP is not necessarily the one with the lowest expected cost for the single-stage model, but rather that program which offers both low cost and the flexibility to be revised when new forecast information becomes available.

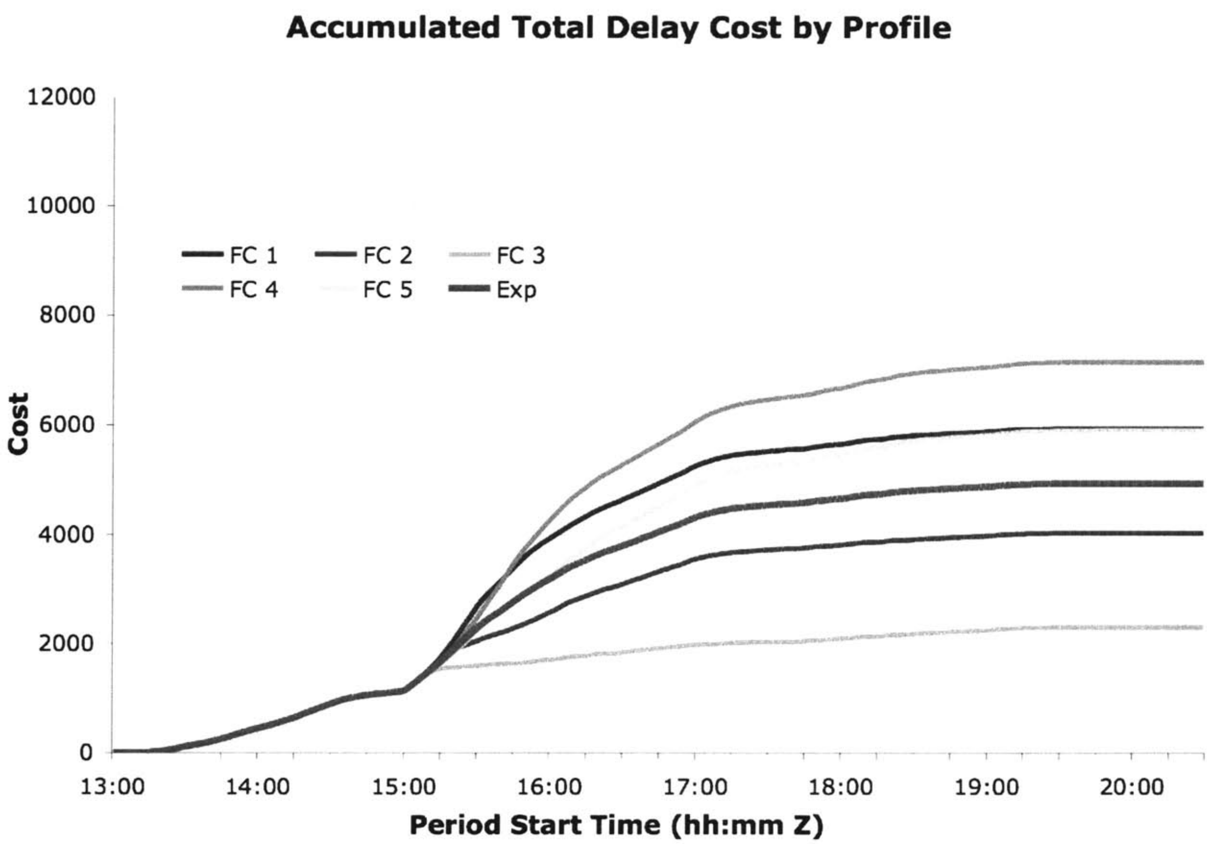


Figure 3-41: Accumulation of total delay cost for the two-stage model

Additional tables and charts for two-stage results can be found in Appendix 1D.

Section 3.5: Summary

In Chapter Three, improvements to GDP decision-making processes are suggested along two separate dimensions: stochasticity and dynamicism. Many different metrics are proposed, each of which addresses, in some way, one or more of the complexities arising from these two dimensions. These metrics, however, are but a small subset of the numerous ways of analyzing the accumulation of delay. The set presented here is neither all-inclusive nor complete. The real contribution of this thesis lies not so much in the specific metrics that are proposed, but in how the delays of a GDP are handled. Airborne delays are calculated for each combination of proposed program and possible capacity profile, resulting in a model that shows not just the average overall result of a proposed GDP, but a set of possible results of that program. The metrics introduced herein show the wealth of possibilities and richness of data that can be placed in the hands of the traffic manager.

Furthermore, there are opportunities for improving these metrics. Throughout the discussion, it is apparent that the quality of information and the timing at which information is acquired is neither homogenous nor discrete; forecasts become gradually become more accurate over time rather than suddenly at t_{pi}. The most aggressive approach, the two stage-model, also has the greatest weaknesses, whereby the required assumptions rarely hold: information about the future is never known with certainty, and if it is, that certainty does not occur for all events at the same, anticipated time. In Chapter Five, the quality of the information available – a theme throughout this thesis – will return as areas of future research are discussed. Chapter Four will describe the inner workings of the model and the calculations that drive the results shown in the figures and metrics of Chapter Three.

Chapter 4: Model Construction

The primary theme of the first three chapters of this thesis is the inclusion of uncertain arrival capacities into the design process of a ground delay program. To this end, Chapter One introduces ground delay programs and uncertainty, Chapter Two describes the various types and sources of uncertainty and then refines the discussion to focus on how probabilistic arrival capacities affect ground delay programs, and Chapter Three proposes metrics that incorporate uncertainty into the evaluation of a program. Underneath these primary stochastic currents, however, there exists a second, less immediate theme that, at their core, ground delay programs are simply an algorithmic approach to manipulating the arrival demand at an airport that otherwise lacks the capacity to accommodate all inbound aircraft. From this perspective, Chapter Two details the mechanisms of this algorithm: the sources of data, input variables, and assignment of ground delays. Chapter Three then summarizes the algorithmic outputs based on the presence of an assumed, underlying analytical tool. Chapter Four now documents the implementation of the ground delay program algorithms in a Microsoft Excel-based tool.

In this penultimate chapter, the assumptions and calculations that underlie the results shown in Chapter Three are presented in an operational order[40]. After an overview of the different aspects of the tool in Section 4.1, the remaining sections each handle a single component and are presented in the order of calculation: Section 4.2 contains information on the input data, Section 4.3 details the modeling of a ground delay program, Section 4.4 assigns delay to flights, Section 4.5 assigns flight arrival times by profile, and Section 4.6 discusses the summarization of data. The final passage, Section 4.7, finishes the discussion on implementation and transitions to the conclusion of this thesis in Chapter Five. The metrics from Chapter Three, which summarize input values, intermediate calculations, and results, are discussed where appropriate.

Section 4.1: Tool Overview

The tool is constructed as a time-based scenario in Microsoft Excel[41]. Specific times are noted for individual flights (for example, scheduled or assigned departure, demand, and arrival times), capacity forecasts (time periods), and the ground delay program itself (slot times, boundaries, and other global variables). For each time increment, the tool processes actions and tracks a system state, including flight status and the airport arrival capacity. Although, for the purposes of this thesis, time is divided into uniform increments of one-minute duration, the tool is otherwise designed to accommodate arbitrary and independent time-step durations.

Interlaced within the time increments, the algorithms used by the tool process information in five steps. First, flight data is used to determine the arrival demand at an airport. Second, PAARs are incorporated with aggregated demand forecasts to identify planned arrival demand times. Third, the flight demand order, exemption classifications, and en route times are

[40] Please note, however, that Chapter Four is not intended to serve as a user's manual for the tool.
[41] Please contact the author for a software copy of the tool

used to determine the corresponding individual flight departures times. Fourth, these proposed departure times are then used in a separate algorithm to identify arrival times for each of the forecast arrival capacity profiles. Fifth, the adjusted, GDP arrival demand order is used to assign forecasted arrival times by flight for each capacity profile. Finally, summary statistics are compiled and reported.

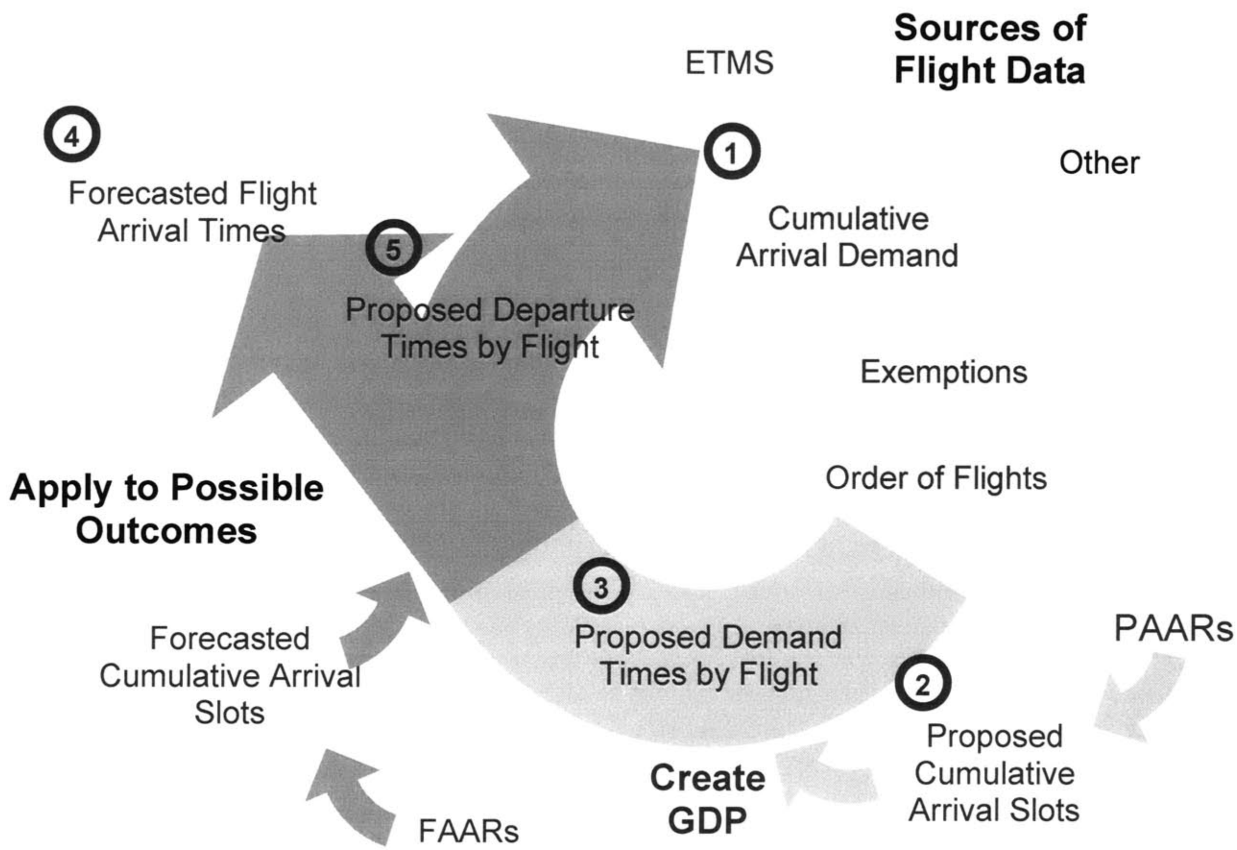


Figure 4.1: Order of calculation in the tool

Section 4.2: Data Requirements and Manipulation

The data required by the tool can be classified into three categories by purpose: ground delay program inputs, the arrival capacity scenario, and miscellaneous information used to modify the algorithms in the tool. In general, data is provided for the tool as a table, or as a specific variable, both of which can be derived from an automated or manual data source.

Section 4.2.1: Flight Data

A sample of the raw flight data used by the tool has been previously shown in Figure 3-2. The data exhibited is taken from ETMS and contains information on flight origination, destination, actual / estimated departure time, estimated arrival time, and other aircraft information such as carrier (by ACID) and aircraft type. In addition to ETMS data, the tool accepts six optional, additional fields to allow the user to customize how a flight is handled by the ground delay program: two fields for ground delay and flight exemption status, three more to specify the cost function used to compare different types of delay, and, lastly, an adjustment time that controls how a flight would respond to changes in the proposed ground delay program. This last field is also referred to as "preparation time."

Before being used by the ground delay program, raw flight data is processed to yield three pieces of additional information (Figure 4-2). First, the en route time (r_f) is calculated as the difference between estimated departure (d_f) and arrival times (a_f). En route time is fixed for ground delay program calculations, but can be updated – and the entire GDP recalculated – whenever new departure or arrival time estimates are obtained from ETMS.

Processed Flight Data

Flight ID	Departure Time (Scd.)	Arrival Time (Scd.)	En Route Time	Exempt?	Arrival Order	Arrival Order*
53A1186	12:37	15:00	2:23	Yes	1	
53A111	12:36	15:02	2:26	Yes	2	
10A305	13:04	15:02	1:58	Yes	3	
47A126	14:03	15:02	0:59	No	4	1
53A529	12:16	15:04	2:48	Yes	5	
01A829	12:30	15:04	2:34	Yes	6	
01A311	12:52	15:04	2:12	Yes	7	
10A321	13:19	15:04	1:45	No	8	2
01A548	13:35	15:05	1:30	No	9	3
27A310	13:03	15:07	2:04	Yes	10	
50A6808	14:08	15:07	0:59	No	11	4
53A379	13:36	15:08	1:32	No	12	5
10A749	13:02	15:09	2:07	Yes	13	
20A1746	13:07	15:10	2:03	Yes	14	
28A963	13:42	15:10	1:28	No	15	6
20A1175	13:01	15:11	2:10	Yes	16	
01A643	12:47	15:12	2:25	Yes	17	
10A803	13:34	15:12	1:38	No	18	7
53A945	06:43	15:13	8:30	Yes	19	
48A46	13:51	15:14	1:23	No	20	8
...						

Time is expressed in hours : minutes
En Route Time is the difference between scheduled arrival and departure times
If a flight is marked as exempt, it is not allocated any ground delay for a GDP
Arrival order* is the order of scheduled arrival for included flights

Figure 4-2: A sample of processed flight data

Second, the set of flights that are included in the ground delay program (**F"**) is defined. This set includes all flights for which data is available (**F**) except for those which are excluded by the traffic manager[42], already airborne, or with an imminent departure time[43] (**F'**). The ability of the TM to manually exclude flights from a program using the tool is a significant change from

[42] Individually, or by departure airport tier (see §4.2.4)
[43] See "pre-departure time" in §4.2.6

current FSM algorithms, under which exemptions for not-yet-departed aircraft are only permitted by airport of origination. By allowing flight-specific exemptions, the tool accommodates both the current methodology and that favored by many proposed approaches to the ground holding problem – modeling individual flights and not groupings restricted only to origination airports.

Third, and most important, the arrival order of each flight is determined, relative to both the set of all flights ($o_{a,f}$) and also, if applicable, to the set of controlled flights ($o_{a,f'}$). The arrival order is later used to assign a flight to available slots for both the planned and forecasted airport arrival rates. Flight arrival order is calculated as a non-repetitive ranking of all estimated arrival times, with ties broken arbitrarily. Please see Appendix 1A for a table of flight data fields and their definitions.

Throughout Chapter Four, notation will be introduced and defined, as necessary. Importation flight data notation includes:

F is the set of all flights:	$\mathbf{F} = \{f_1 \ldots f_F\}$
F' is the set of exempt flights	
F" is the set of included, or non-exempt, flights:	$\mathbf{F} = \mathbf{F'} \cup \mathbf{F''}$
d is the set of all scheduled flight departure times d_f:	$\mathbf{d} = \{d_{1 \ldots} d_F\}$
w is the set of all scheduled flight demand times w_f:	$\mathbf{w} = \{w_{1 \ldots} w_F\}$
a is the set of scheduled flight arrival times a_f:	$\mathbf{a} = \{a_{1 \ldots} a_F\}$; $w_f = a_f \; \forall \; f$
r is the set of scheduled en route times, or flight durations r_f:	$\mathbf{r} = \mathbf{w} - \mathbf{d}$
$o_{a,f}$ is the rank order of flight f within **a**	

Section 4.2.2: Time and Airport Acceptance Rates

The tool assumes that there will be at least two arrival capacity profiles: a reference, base capacity profile, which is the maximum number of arrivals expected for an airport under optimal conditions, and a "GDP" profile, which contains the PAARs for the ground delay program. Additional capacity profiles, which are composed of forecast arrival acceptance rates, or FAARs), are required for any of the probabilistic analyses and must be specified as part of a capacity scenario. The table in Figure 4-3 shows the base and GDP profiles (shaded), as well as the capacity scenario (unshaded) used for the examples in this thesis. All capacity profiles in the scenario have a positive likelihood adding to 100% for the scenario. By convention, the base and GDP profiles serve as a reference and are assigned a likelihood of 0%

Capacity Profiles		
Profile	Likelihood	Description
Base	0%	Base Capacity Scenario
GDP	0%	Proposed GDP
FC 1	40%	Heavy Rain
FC 2	30%	Light Rain
FC 3	15%	No Rain
FC 4	10%	Delayed Heavy Rain
FC 5	5%	Very Delayed Heavy Rain

Figure 4-3: Arrival Capacity Scenario

The profile capacities are specified for each time period. Although, for calculation purposes, the periods do not necessarily need to be of uniform size, the example in this thesis contains periods with a uniform duration of 15 minutes[44].

[44] $dur_i \equiv Dur \equiv 15$ minutes (for the example presented in this thesis)

A simplified formula is:

$$\text{TimePeriod}_i = \text{TP}_i = [\text{TPStart}_i, \text{TPEnd}_i)$$

$$\text{TPStart}_i = t_s + (i-1) \times \text{Dur} \qquad (f4.1)$$

$$\text{TPEnd}_i = \text{TPStart}_i + \text{Dur} \qquad (f4.2)$$

where
t_s is the global start time of the simulation
Dur is the global time period duration

Figure 4-4 shows the table of arrival rates, defined as arrival capacity per period[45], that corresponds to the chart of capacities illustrated in Figure 3-1. The PAARs can be found in the column that corresponds to "GDP" and the FAARs are listed for each profile of the capacity scenario. The tool assumes that PAARs are provided by the traffic manager and that FAARs are obtained from a future resource that translates meteorological forecasts into a capacity scenario.

Arrival Capacity per Time Period

Time	Base	GDP	FC 1	FC 2	FC 3	FC 4	FC 5
15:00	**25**	**15**	**10**	**20**	**25**	**25**	**25**
15:15	25	15	15	20	25	25	25
15:30	25	20	15	20	25	10	25
15:45	25	20	20	20	25	15	25
16:00	25	20	20	20	25	15	10
16:15	25	20	20	20	25	20	15
16:30	25	20	20	20	25	25	17
16:45	25	25	25	20	25	25	25
...							

Capacity is expressed in aircraft
Time refers to the starting time of each period
Time is expressed in hours : minutes
Capacities in **bold** are shown by slot in Fig. 4-6

Figure 4-4: Arrival Capacities by Time

Section 4.2.3: Arrival Slots

In FSM, slots are defined as a period of time in which the arrival capacity of the airport is one aircraft (*f*2.1 in §2.3.1). For a large airport, of total arrival capacity between 60 and 120 aircraft / hour, a typical arrival slot will be between 0.5 and 1 minute in duration. Correspondingly, as the PAARs change over the course of a day, slot durations will also change. The tool, however, approaches slots slightly differently: to accommodate a time-based simulation, slots are used as the basis for time steps and, instead, have a fixed duration. The slot duration is a global variable set by the user, with variable capacity.

$$\text{Slot}_t = [\text{SStart}_t, \text{SEnd}_t)$$

$$\text{SStart}_t = t_s + (t-1) \times \text{SlotDur} \qquad (f4.3)$$

$$\text{SEnd}_t = \text{SStart}_t + \text{SlotDur} \qquad (f4.4)$$

where
SlotDur is the duration of each slot, which is assumed to be equal to one minute

[45] Arrival capacity rates must take integer values

$$C_{t,c} = \left[\sum_{n|n<p} FAAR_{n,c} + \frac{SStart_t - TPStart_p}{Dur} \times FAAR_{p,c} \right] - \sum_{n|n,t} C_{n,c} \qquad (f4.5)$$

where
Time Period p is the latest time period to start at or before $SStart_t$
$C_{t,c}$ is the capacity of slot t for profile c (for the GDP slots, replace $FAAR_{i,c}$ with $PAAR_i$)
$FAAR_{i,c}$ is the FAAR of time period i for profile c
Dur is the global time period duration

A sample calculation of slot capacities is shown in Figure 4-5. In this example, a period has 15 slots and 20 planned arrivals, or 1.33 arrivals/slot. The cumulative slot capacity is the cumulative number of planned arrivals rounded to the next highest integer.

Slot	Cumulative Arrivals	Slot Capacity Cum.	Slot Capacity Each
1	1.33	2	2
2	2.67	3	1
3	4.00	4	1
4	5.33	6	2
5	6.67	7	1
6	8.00	8	1
7	9.33	10	2
8	10.67	11	1
9	12.00	12	1

Arrivals/Period	20
Slots/Period	15

Figure 4-5: Sample calculation of arrival slot capacities

Arrival Capacity per Slot

Time	Base	GDP	FC 1	FC 2	FC 3	FC 4	FC 5
15:00	2	1	1	2	2	2	2
15:01	2	1	1	1	2	2	2
15:02	1	1	0	1	1	1	1
15:03	2	1	1	2	2	2	2
15:04	2	1	1	1	2	2	2
15:05	1	1	0	1	1	1	1
15:06	2	1	1	2	2	2	2
15:07	2	1	1	1	2	2	2
...							

Capacity is expressed in aircraft
Time refers to the starting time of each slot
Time is expresed in hours : minutes

Figure 4-6: Sample arrival slots and their capacities

The table in Figure 4-6 shows a sample of the slots and slot capacities used in the tool. As shown, each "slot" has duration of one minute and variable capacity that depends on the arrival acceptance rates shown in Figure 4-4.

It should be noted that the use of fixed-duration, variable-capacity slots is different from the calculations in FSM as, for very small arrival rates, the FSM slots will become proportionately large, while those in the tool will retain their size with many simply having a capacity of zero. However, for airports of any reasonable capacity – those that might require a GDP – this difference is minimal[46]. In fact, the slot approximation facilitates ground delay program calculations by, first, simplifying the number of slots, as the tool only needs to track the individual capacities, and, second, reducing the required precision of forecast demand times to the minute, instead of to the second.

[46] The slots used by FSM are also approximations

Section 4.2.4: Origination Airports

In addition to exemptions given to individual flights, the tool can also exempt flights based on their airport of origination, similar to the process currently used in FSM. The tool accepts a table of origination airports, listed by airport code, and a field to indicate the exemption status of flights from these airports. All flights from airports that are marked as exempt in the list are excluded from the GDP, as are those from airports omitted from the list entirely[47]. A list of all airports from which flights in the sample data set originate is included in Appendix 1B.

Section 4.2.5: Cost Structures

As discussed in §3.3.2, the tool is able to provide both cost-based and delay-based summaries of a ground delay program. The tool assumes that the cost of one unit of a particular type of delay to a particular flight may be dependent on the total amount of delay of that type that is experienced by that flight. Therefore, the cost of delay is calculated for each flight and aggregated as a total cost. Please note that this assumption is different from many previous approaches to delay costing in that, although a constant cost ratio is allowed by the tool, it is not required. Furthermore, the use of three functions for the delay of each flight greatly complicates approaches to optimize the decision of the traffic manager. To this point, the calculation of delay cost in this thesis will need to be simplified to extend this work in the direction of mathematical optimization modeling.

To transcribe delays into cost, the tool uses a piecewise linear function of the time of delay, as specified by delay-cost pairs. Unspecified values are calculated as a linear interpolation. It is assumed that three types of delay cost may be accumulated by a flight[48]:

General Delay Cost – XDC(t): General delay costs are those associated with a minute of delay regardless of how or where that delay occurs. For example, general delay costs include the cost of labor of flight personnel and disruption to network schedules.

Ground Delay Cost – GDC(t): Ground delay costs are those that occur only for ground delays, an example of which would be the opportunity cost of occupying a gate. In the example used in this thesis, however, the ground delay cost function is zero.

Air Delay Cost – ADC(t): Air delay costs are those that only occur for flights in the air, and are primarily a function of the cost of fuel and the maintenance cost of additional flight hours.

For each flight, the traffic manager provides three cost function variables (§4.1.2) that specify the form of the function to be used for each type of delay – while there are three general types of delay cost, each flight can have its own cost function for each type.

Although traditional air and ground delay costs were previously discussed as being separable entities, the total cost function shows that they are not. A primary component of total cost is the cost of general delay (XDC), which is a function of the cumulative time of ground and air delay. In order to explicitly allocate total costs as being "ground" or "air", general costs must

47 The user also has an option of including flights from omitted airports

48 There are **two** general types of delay, however, air and ground. The third cost type is used to capture costs that occur irrespective of these types

also be allocated. However, as the incremental cost of a minute of delay increases with the amount of delay, the full cost of delay cannot be assigned as air- (or ground-) related, because it is the total amount of delay that drives this incremental increase.

In the simple example used for this thesis, a single delay function is used for each type of delay for all aircraft. Figure 4-7 illustrates the three cost curves that have been provided to the tool[49]. Please note that, for the approximation previously shown in Figure 3-28, the overall costs of ground delay can be conceived as the sum of the GDC(t) and XDC(t) functions, while the overall cost of air delay is the sum of ADC(t) and XDC(t). As will be shown in §4.5.1, however, delay costs are calculated separately to allow for non-linear forms of the cost functions.

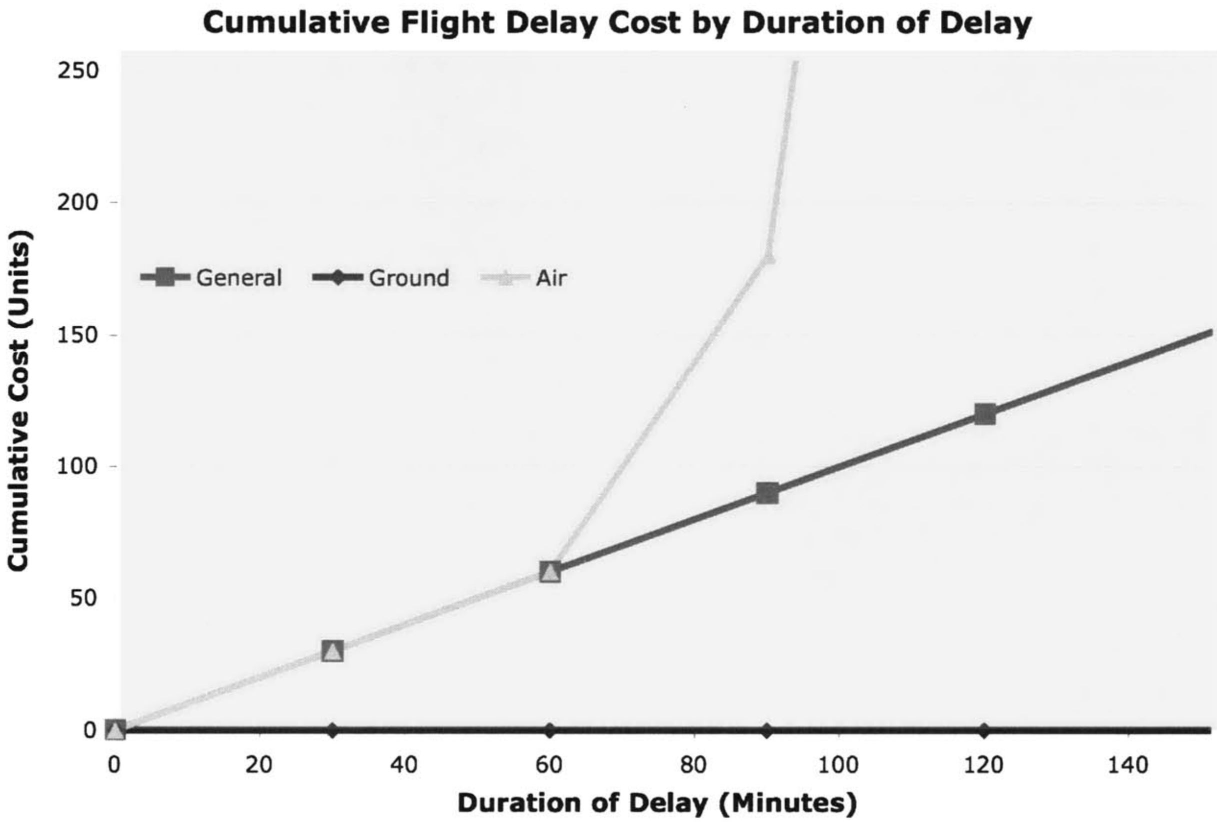


Figure 4-7: Air, ground, and total cost functions

Section 4.2.6: System Variables

For the wide array of analyses described in Chapter Three, the tool requires two sets of additional variables. The first set contains three variables that establish the environment of the tool. They include the GDP implementation time (t_i), which is used to determine included flights, the GDP start time (t_s) (§2.3.2), and the time, if any, that an updated arrival capacity forecast is expected (t_u). The second set consists of two variables that support the ground delay program algorithms: the slot duration time (if fixed) and a buffer time used to exempt flights whose scheduled departures are close to the current time.

[49] The cost functions have been named "Air", "Ground", and "General"

Type	Source	Example
Flight	ETMS	Scheduled aircraft departure and arrival times, ACIDs, origination, current flight status
Flight	TM	GDP exemption status
Flight	n/a	Preparation time
GDP	TM	GDP start and implementation times, PAARs, buffer times
Capacity	n/a	Capacity scenarios (profiles, FAARs, and likelihoods), forecast update times
Simulation	TM	Slot durations
Other	n/a	Cost function parameters

"n/a" refers to inputs whose ultimate sources have not yet been determined

Figure 4-8: A summary of types of flight input data and their sources

Section 4.3: Modeling a Ground Delay Program

A ground delay program attempts to assign ground delays to flights such that a flight reaches an airport when there is available capacity for that flight to land. In this manner, delays are computed by working backwards from the planned flight demand times, which are based on the PAARs and scheduled arrival demand at an airport. The first element of a ground delay program provides this calculation of flight demand times and is performed in the tool by the Planned Arrivals Model.

Section 4.3.1: The Planned Arrivals Model

The first step of the Planned Arrivals Model is to identify the PAAR slots available to flights that are included in the GDP. It would seem natural to use the slots as defined by the PAARs (see *f*4.5) that are shown in Figure 4-6. These planned slots, however, do not account for exempt flights, which are given first priority for the available capacity. The Planned Arrivals Model, therefore, first processes exempt flights through a simple queuing model to identify which slots will be consumed by flights not included in the program. This queuing model is time-based, with the time increment equal to the duration of a slot. As discussed in §4.2.3, the tool uses slots that have a fixed duration with variable, integer capacity. The formulae used to process the exempt queue are:

$$Q_t' = D_t' + Q_{t-1}' - A_t' \qquad (f4.6)$$

$$A_t' = \mathrm{Min}\left(Q_{t-1}' + D_t', C_t\right) \qquad (f4.7)$$

where

Q_t' is the size of the queue of exempt aircraft at the end of step t ($Q_0' = 0$)
D_t' is the number of exempt aircraft that are scheduled to demand arrival during step t
A_t' is the number of exempt flights that are planned to arrive during step t
C_t is the planned raw arrival capacity of slot t, as defined by the PAARs

Please see Figure 4-9 for an example of how flight queues and arrivals are calculated.

For flights included in the ground delay program, the remaining available capacity is the original capacity less capacity consumed by arrivals of exempt flights.

$$\overline{C}_t = C_t - A_t' \qquad (f4.8)$$

where
$\overline{C}_t$ is the arrival capacity of slot t available to flights included in a GDP (**F"**)

The second step of the Planned Arrivals Model is to identify the number of planned flight arrivals over time. As A_t', calculated previously, is the number of exempt arrivals that occur by time t, the non-exempt arrivals (A_t'') can be found using a similar queuing model with parameters (Q_t'', D_t'', A_t'' and $\overline{C}_t$).

As a third and final step, the planned cumulative arrivals of included flights by step are also computed[50]:

$$\Lambda_t'' = \Lambda_{t-1}'' + A_t'' \qquad (f4.9)$$

where
Λ_t'' is the cumulative number of included, planned arrivals through step t

We also define V_t'' as the cumulative scheduled arrival demand of included flights through step t (note that $V_t'' \geq \Lambda_t''\ \forall\ t$, which is easily proven). Please see Appendix 2 for sample screen images of slot assignment in the tool.

Section 4.3.2: Delay Assignment

The next step in a ground delay program is to assign a planned arrival time to each flight. Recall, however, that the planned arrival acceptance rates that were used to determine the slots may never be realized and that they simply propose the rate at which flights will reach the destination airport and request to land. As a result, the tool treats these "planned arrival" times as planned *demand* times (ω_f), or the time at which a flight will be assumed to be available to land at an airport. Any applicable airborne delay will only be assigned later, once the specific arrival demand times of all flights have been determined. (Forecast arrival times ($\alpha_{f,c}$) will be derived based on the FAARs in §4.4.)

As exempt flights are assigned slots first, demand times for exempt and included flights must be determined separately. For exempt flights, demand time is simply the scheduled arrival time (a_f). For included flights, the demand time is the first available slot at or after the original scheduled arrival time. As the Planned Arrivals Model has already determined which slots will be assigned to included flights (Λ_t''), flights can be assigned slots on a FCFS-basis, determined by the original scheduled arrival order of each flight ($o_{a,f}$). In this way, each flight is assigned a slot in order at or after the original scheduled flight arrival time. (Please see Figure 4-10.) Once the demand times have been calculated, both exempt and included flights will be treated similarly and there is no longer a need for a distinction between the two.

[50] Note that the Planned Arrivals Model only computes aggregate slot usage and does not track individual flights

	Arrival			Arrivals	
Slot	Capacity	Demand	Queue	Slot	Total
1	2	1	0	1	1
2	1	1	0	1	2
3	1	1	0	1	3
4	2	2	0	2	5
5	1	2	1	1	6
6	1	2	2	1	7
7	2	1	1	2	9

Figure 4-9: Cumulative flight arrivals by slot

For Included Flights		
Flight	Demand Order	Assigned Slot
Flt1	1	1
Flt2	2	2
Flt3	3	3
Flt4	4	4
Flt5	5	4
Flt6	6	5
Flt7	7	6

Figure 4-10: Flight arrival slot assignments

$$\omega_f = \begin{cases} a_f & \forall f \in F' \\ \arg\min t \;\middle|\; \Lambda_t'' \geq o_{a,f''} & \forall f \in F'' \end{cases} \qquad (f4.10)$$

where

ω_f is the demand time of flight f as defined by the GDP; for **F"**, ω_f is the smallest slot time t such that Λ_t" (cumulative arrivals) $\geq o_{a,f'}$ (the order of planned arrival for f)

$o_{a,f}$ is the rank order of flight f within scheduled arrival times **a**

The last step in creating a program is to calculate the ground delays (γ_f) and departure times (δ_f) proposed by the GDP for each flight. Although there is more than one way to calculate the set of flight ground delays, or $\boldsymbol{\gamma}$, the tool first determines the proposed departure time as demand time less time en route for each flight. Therefore, γ_f is the difference between scheduled and proposed departure times, or the ground delay that is assigned to each flight by the proposed GDP. Note, that this calculation assumes that the taxi and en route times will be independent of whether or not a GDP is in effect – an assumption that has already been made by the algorithms that determines cumulative and flight-specific arrival times.

$$\delta_f = \omega_f - r_f \qquad (f4.11)$$

$$\gamma_f = \delta_f - d_f \qquad (f4.12)$$

$$g_t = \sum_{f|\delta_f \leq t} 1 - \sum_{f|d_f \leq t} 1 \qquad (f4.13)$$

$$G_t = \text{SlotDur} \times \sum_{n \leq t} g_n \qquad (f4.14)$$

where

δ_f is the proposed departure time of flight f

γ_f is the proposed ground delay assigned to flight f

g_t is the number of flights under ground hold during step t

G_t is the cumulative ground delay time up to and including step t

Section 4.4: Profile Outcomes

The algorithm that calculates demand times is similar to that in FSM. Once these times have been assigned, however, the tool diverges from FSM and forecasts the arrival time for each flight by capacity profile. Forecasted arrival times ($\alpha_{f,c}$) are defined as the time a flight f will actually arrive given a proposed demand time and the realization of a capacity profile c. To this end, arrival times are forecasted by the same queuing process as that described in §4.3.1 and §4.3.2, repeated for each profile. For arrival times, however, there is no need to distinguish between exempt and included flights because all flights are treated equally once airborne.

First, the cumulative arrivals ($\Lambda_{t,c}$) are calculated using a FCFS queue with slot-based time steps, PAAR-based capacities ($C_{t,c}$), and cumulative flight arrival demand (Δ_t):

$$Q_{t,c} = D_t + Q_{t-1,c} - A_{t,c} \qquad (f4.15)$$

$$A_{t,c} = \mathrm{Min}\left(Q_{t-1,c} + D_t, C_{t,c}\right) \qquad (f4.16)$$

$$\Lambda_{t,c} = \Lambda_{t-1,c} + A_{t,c} \qquad (f4.17)$$

$$\Delta_t = \Delta_{t-1} + D_t \qquad (f4.18)$$

where
$Q_{t,c}$ is the size of the airborne queue of aircraft at the end of step t ($Q_{0,c} = 0$) for profile c
$A_{t,c}$ is the number of flights that arrive during step t in profile c
$C_{t,c}$ is the arrival capacity of slot t in profile c
D_t is the number of aircraft that are scheduled to arrival during step t
Δ_t is the cumulative number of scheduled arrivals through step t (note: $\Delta_t \geq \Lambda_{t,f}\ \forall$ t, f)
$\Lambda_{t,c}$ is the cumulative number of arrivals through step t

Second, the individual profile-dependent arrival times and associated flight delays are calculated using the flight demand time orders ($o_{\omega,j}$) and the cumulative profile arrivals.

$$\alpha_{f,c} = t \mid \Lambda_{t,c} = o_{\omega,f} \qquad (f4.19)$$

$$p_{f,c} = \alpha_{f,c} - \omega_f \qquad (f4.20)$$

$$\tau_{f,c} = \gamma_f + p_{f,c} \qquad (f4.21)$$

$$P_{t,c} = \mathrm{SlotDur} \times \sum_{n \leq t} Q_{n,c} \qquad (f4.22)$$

where
$\alpha_{f,c}$ is the estimated arrival time of flight f under forecast profile c
$o_{\omega,f}$ is the rank order of flight f within demand times $\boldsymbol{\omega}$
$p_{f,c}$ is the airborne delay of flight f under profile c
$\tau_{f,c}$ is the total delay of flight f under profile c
$P_{t,c}$ is the cumulative airborne delay by slot time t under profile c

Once the flight arrival times have been determined, the summary statistics (§3.2.4) and H3 metrics (§3.3.4) previously discussed are computed from the sets of flight arrival ($\boldsymbol{\alpha}_c$) and delay ($\boldsymbol{\gamma}$, $\mathbf{p}_c$, $\boldsymbol{\tau}_c$) times.

Section 4.5: Auxiliary Functions

In addition to the delay experienced by each flight, the tool also calculates two additional quantities for each flight and outcome.

Section 4.5.1: Delay Costs

The first quantity is the cost of delay. In §4.2.5, cost is discussed from the data perspective, whereby the tool requires (cost, time) pairs and linearly interpolates intermediate points. The points determining the form of the functions provided for the examples in this thesis are shown in Figure 4-11.

As expected, for each type of delay, the tool simply looks up the amount of delay in the first column and finds the cost value in the column corresponding to the appropriate function. When the amount of delay is not contained in the table, the cost function assumes a linear relationship between the next highest and lowest values, or:

	Cumulative Cost		
Delay	General	Ground	Air
0	0	0	0
60	60	0	60
90	90	0	180
1000	1000	0	18,380

Air delay cost increases at rates of 1:1, 4:1, and 20:1

Figure 4-11: Raw Cost Function Inputs

$$\text{Cost}_x(t) = \text{Cost}_x(t_-) + (t^+ - t_-) \times (\text{Cost}_x(t^+) - \text{Cost}_x(t_-)) \qquad (f4.23)$$

where
t is time of delay, in minutes
t_- is the greatest time less than or equal to t for which a cost is explicitly defined
t^+ is the earliest time greater than or equal to t for which a cost is explicitly defined
x refers to the appropriate cost function: ADC(t), GDC(t), XDC(t)

Recall that the tool accounts for three types of delay: ground, airborne, and general. The total delay cost for a flight is dependent on the capacity profile and is defined as:

$$DC_{f,c} = ADC(p_{f,c}) + GDC(g_f) + XDC(\tau_{f,c}) \qquad (f4.24)$$

where
$DC_{f,c}$ is the total delay cost for flight f under forecast profile c

Section 4.5.2: Avoidance Time

The second factor calculated by the tool is avoidance of delay. While delay cost is used to aggregate different types of delay, delay avoidance – the concept of by when and how much air or ground delay could be reduced if a proposed program is strengthened or weakened – keeps air and ground delay separate because of the inherent tradeoff between them.

Airborne Delay Avoidance

For a given flight, airborne delay can only be avoided while that flight is still on the ground. Therefore, the amount of unavoidable airborne delay for a flight ($AAv_{f,c}(t)$) can be conceptualized as a step function whose step location is determined by proposed departure time and step magnitude by the anticipated airborne delay.

$$AAV_{f,c}(t) = p_{f,c} \quad \forall t > \delta_f \quad (\text{otherwise } 0) \tag{f4.25}$$

$$TAAv_c(t) = \sum_{f \in F} AAv_{f,c}(t) \tag{f4.26}$$

where

$AAv_{f,c}(t)$ is the unavoidable air delay for a flight f under forecast profile c at time t
$TAAv_c(t)$ is the cumulative unavoidable air delay for a forecast profile c at time t

A limitation of this formulaic approach to unavoidable delay is that the calculations do not show the effects of holding the flight, i.e. the air delay in question may be avoided only to result in air delay at a later time when the flight is actually released from the ground hold. Furthermore, it does not consider the effects of allowing a given flight to depart while holding a flight with a similar arrival time but later departure time, which would postpone the accumulation of the first flight's unavoidable delay. A more accurate interpretation of the function for unavoidable air delay shown here is the air delay that will be incurred by flights given a time of action, forecasted outcome, and lack of any revision to the ground delay of flights with forecasted arrival times at or before the flight in question.

Ground Delay Avoidance

For each flight, previously assigned ground delay can be avoided if a program is revised before the proposed departure time of that flight, assuming that the revision cancels the ground delay for the flight in question. The amount of ground delay that is avoided depends on two principal factors: when a ground delay program is revised (t) and how quickly a flight can react to the revision ($prep_f$).

$$GAv_f(t) = \max(0, \min(t + prep_f, \delta_f) - \omega_f) \tag{f4.27}$$

$$TGAv(t) = \sum_{f \in F} GAV_f(t) \tag{f4.28}$$

where

$GAv_f(t)$ is the unavoidable ground delay for a flight f at time t
$prep_f$ is the preparation time of flight f
$TGAv(t)$ is the cumulative unavoidable ground delay at time t

Preparation time refers, in principle, to the amount of time that a flight requires to take-off once a program revision is implemented, which includes both the time to inform a flight of the revision and the time a flight needs to leave the gate, taxi and depart. Within ETMS, the taxi time is also called "ground time" and modeled as the difference between gate and wheels-up departure times. Ground time is used in the forecasting of arrival demand times for individual flights (see §2.2.2). Preparation time can vary by flight due to differences in the departure airports and current flight status, for example, whether an aircraft has been boarded or whether it has already left the gate. Ultimately, it is expected that the preparation time will be relatively small for most aircraft and that the required time could be modeled and provided by ETMS, although this capability does not currently exist. For the purposes of the example contained in this thesis, preparation time has been fixed at 10 minutes per flight.

Section 4.6: The Two-Stage Model

Recall from §3.4 that the two-stage model allows the traffic manager to see how a ground delay program with uncertain arrival capacities would perform given an anticipated update to the capacity scenario. It is assumed that the updated forecast will indicate, with certainty, which of the possible capacity profiles will occur and that, at the time of update, the PAARs will be revised to reflect the appropriate outcome. The two-stage model creates a deterministic ground delay program at a future time (t_u: the update time) for each forecasted capacity profile.

To project the decision environment at the update time, the tool first uses the proposed program to assign demand times and then revises the times as if the program would be cancelled at the time of the forecast update (see Figure 4-12). The affect of assuming the cancellation of the original program is that it allows the tool to mirror the environment that would exist if the proposed program were to be enacted and revised, using the global time variable to track which flights would be en route and on the ground at the time of the update given the original schedules and proposed GDP. As would be expected, this calculation is very similar to that used for unavoidable ground delay; the revised demand time for each flight (δ^*_f)[51] is the lesser of (1) the proposed demand time and (2) the update time plus en route time plus preparation time.

$$\delta^*_f = \min(\delta_f, t_u + r_f + prep_f) \qquad (f4.29)$$

where
δ^*_f is the revised demand time of flight f
$\Delta^*_t = \sum f \mid \delta^*_f = t$ is the revised cumulative arrival demand of aircraft during step t
t_u = expected update time

Furthermore, just as with the GDP, flights must also be partitioned into an exempt and an included set. The exempt set (**F*'**) consists of all flights in **F'** plus those flights that have departed or have imminent departure times at t_u; the included set consists of all other flights.

F*' is the set of exempt flights at t_u; $\mathbf{F'} \subseteq \mathbf{F^{*\prime}}$
F*'' is the set of included flights at t_u
$\mathbf{F} = \mathbf{F^{*\prime}} \cup \mathbf{F^{*\prime\prime}}$

Once the revised demand times and flight sets that result from the cancellation of the original GDP have been calculated, the tool can model a new, deterministic program at t_u for each of the

[51] δ^*_f actually represents the earliest time at which a flight could demand arrival given the initial program and an expected revision; as the GDP is assumed to become a deterministic problem at t_u, the intermediate use of demand times for included flights is no longer necessary

possible capacity profiles ($c^* \in \Omega^*$)[52]. Just as in §4.3.1, each program is a two-phase queuing model, with the first queue using parameters (Q^*_{t,c^*}'', Δ^*_t'', A^*_{t,c^*}'' and C^*_{t,f^*}) and the second with (Q^*_{t,c^*}', Δ^*_t', A^*_{t,c^*}' and $\bar{C}^*_{t,c^*}$). From the outputs of the second queue, individual flight departure and arrival times can be derived and the two-stage performance of the original proposed ground delay program evaluated.

The table in Figure 4-10 illustrates the revision of demand times for a two-stage GDP. For the original program proposed at 13:00 Z, there are 8 flights that are included in the program and assigned small amounts of delay. For the two-stage model, we assume that at 14:00 Z new information will become available about the capacity of the airport – by this time, all but three of the included aircraft (in bold) will have departed. The first step to the two-stage model is to revise the flight departure and demand times as they would be if the original GDP was cancelled: for two aircraft (47A126 and 50A6808), the revised departure time reverts back to the original schedule, and for the third aircraft (48A46), whose departure has already been delayed past the scheduled time, 14:00 Z is used. Using these revised demand times, a new GDP (not shown) is then proposed for each of the possible capacity profiles in the revised forecast scenario, just as with the original program in §4.3.

	Original GDP at 13:00			Revised at 14:00		
	Departure		Departure		**Revised** Times	
Flight ID	Time Scd.	Exempt?	Time Prop.	Exempt?	Departure	Demand
53A1186	12:37	Yes	12:37	Yes	12:37	15:00
53A111	12:36	Yes	12:36	Yes	12:36	15:02
10A305	13:04	Yes	13:04	Yes	13:04	15:02
47A126	**14:03**	**No**	**14:09**	**No**	**14:03**	**15:02**
53A529	12:16	Yes	12:16	Yes	12:16	15:04
01A829	12:30	Yes	12:30	Yes	12:30	15:04
01A311	12:52	Yes	12:52	Yes	12:52	15:04
10A321	13:19	No	13:29	Yes	13:29	15:14
01A548	13:35	No	13:45	Yes	13:45	15:15
27A310	13:03	Yes	13:03	Yes	13:03	15:07
50A6808	**14:08**	**No**	**14:19**	**No**	**14:08**	**15:07**
53A379	13:36	No	13:48	Yes	13:48	15:20
10A749	13:02	Yes	13:02	Yes	13:02	15:09
20A1746	13:07	Yes	13:07	Yes	13:07	15:10
28A963	13:42	No	13:53	Yes	13:53	15:21
20A1175	13:01	Yes	13:01	Yes	13:01	15:11
01A643	12:47	Yes	12:47	Yes	12:47	15:12
10A803	13:34	No	13:44	Yes	13:44	15:22
53A945	06:43	Yes	6:43	Yes	6:43	15:13
48A46	**13:51**	**No**	**14:07**	**No**	**14:00**	**15:23**
...						

Time is expressed in hours : minutes
If a flight is marked as exempt, it is not allocated any ground delay for a GDP

Figure 4-12: Calculation of revised demand times for the two-stage GDP

[52] The example in this thesis uses the same capacity profiles at t_u; however, the two-stage model can use any new capacity scenario Ω^*, as long as the outcome of Ω^* is assumed to be known with certainty at t_u

As a final note about the two-stage model, the algorithm by which the GDP revision is made is repeatable. That is, if the forecast at t_u is part of a scenario tree (see §3.4.1), the tool could be used to model the performance of the system and decisions that will be faced by the TM over an infinite number of states by iteratively calculating δ^*_f and $\mathbf{F}^*$.

Section 4.7: Summary

Chapter 4 describes the detailed calculations performed by the tool. In addition to the ability to deal with stochastic capacity scenarios, the tool contains a number of additional features. First, §4.2.1 shows how the tool can provide the traffic manager with greater control over the exemption status and assignment of ground delay for specific flights. While the examples shown refer to a GDP run under the current capabilities of FSM, the additional controls can be added in a manner that provides for more precise program design by, for example, creating a ground delay program that applies to different regions at different times.

Second, §4.6 shows how FSM could be adapted to analyze the two-stage performance of a ground delay program. A GDP is a tool used in a dynamic environment and forecasts of its performance should be equally dynamic. Using the same data as for the static model, a two-stage forecast shows how a ground delay program can perform significantly better (or worse) than expected once the future adjustments of the TM are considered.

With a final summary of the algorithms and their contributions to the management of aviation traffic, Chapter Four completes the description of the tool as a collection of algorithms, queuing models, and time-based scenarios that model a ground delay program. Ultimately, however, the algorithms presented herein have only a limited ability to capture the true, dynamic nature of an ATFM technique that is used to address weather-related delays before the weather event itself is even realized. Chapter Four also broaches an important topic, that further improvements in the performance of ground delay programs will result, to a great extent, from the algorithms used to project how this dynamic system will evolve over time. Chapter Five will continue in this vein and explore the types of algorithms that future research could develop.

Chapter 5: Conclusion

Chapters One through Four document a prototype GDP decision support tool that was constructed during the summer of 2005. This tool represents a significant improvement over existing software capabilities, providing and displaying information that may assist traffic managers in evaluating a proposed GDP under stochastic and dynamic conditions. Chapter Five discusses areas in which additional research is being or could be conducted to further improve the effectiveness of ground delay programs in decreasing the cost of delays and increasing safety in the NAS.

Section 5.1: Summary

The principal subject of this thesis is the incorporation of uncertain arrival capacities into the evaluation of a proposed GDP. The current version of FSM allows the traffic manager to consider only a single arrival capacity profile as both the proposed GDP arrival rate and the actual rate that will occur. However, as discussed in Chapter Two, recent advances in weather forecasting technology may soon allow for the creation of probabilistic arrival capacity forecasts, which will provide a set of discrete arrival capacity profiles with associated likelihoods of occurring. In Chapter Three, such a probabilistic capacity scenario is used as part of a stochastic GDP-planning tool to analyze a proposed program. Three potential improvements over current practice are of particular interest.

First, the proposed GDP planning tool models the arrival of flights for each of the discrete forecast arrival capacity profiles with a FCFS queue. The use of flight arrival queues allows the tool to forecast the airborne delays that would result from a proposed program. As opposed to FSM, which disregards the possibility of airborne delay, the tool calculates these delays to better illustrate the penalty for under-controlling aircraft during inclement weather. Furthermore, the tool uses a set of delay cost functions to combine airborne and ground delay time into a single delay cost, which can be used to compare proposed alternatives.

Second, the tool models the outcome of each forecasted arrival capacity profile separately. In this way, the tool addresses uncertainty in arrival capacity by assigning to the outcome of each profile a likelihood of occurring and by tracking each potential result. Considering separate outcomes improves upon current practice (using a single forecast) by allowing the traffic manager to consider unlikely, but highly unfavorable, outcomes, which may pose an unacceptable safety risk but might otherwise be obscured if simply "averaged" along with the costs of other profiles. Using the tool, the traffic manager can decide whether a program that allows more aircraft to depart is worth the risk of increased airborne delay under these worst-case outcomes.

Third, the tool has additional capabilities to allow the traffic manager to explore dynamic conditions in which the status of flights and available arrival capacity information changes over time. A key point discussed in Chapter Two is the tradeoff among considerations of timing, power of intervention, and availability of information: over time, the traffic manager gains information about the future arrival capacity of an airport, but loses the ability to control flights as they depart. To assist with the appraisal of this tradeoff, the tool reports the amount of delay that will occur if further action is not taken by the traffic manager by a given time, a statistic called unavoidable delay. Furthermore, the traffic manager can use the tool to construct hypothetical future scenarios, in which the tool assumes specified aircraft departure schedules and revised capacity forecasts and indicates how a proposed GDP would perform for each arrival capacity profile.

The stochastic aspects and dynamic nature of a GDP raises important questions about future research, which will be explored in the following section.

Section 5.2: Areas for Future Research

The principal focus of the tool described here has been on the incorporation of arrival capacity uncertainty into the evaluation of a proposed GDP. Further work to improve the development and use of ground delay programs could take one of two forms: first, improvements to the methods by which proposed GDPs are evaluated and, second, the design of algorithms to suggest improved or optimal GDPs to the traffic manager.

Section 5.2.1: Improvements to the Evaluation of a GDP

Incorporate Additional Sources of Uncertainty into GDP Planning Tools

The tool was developed to incorporate arrival capacity uncertainty into the process of evaluating a program. As outlined in §2.2.1, however, there are additional sources of uncertainty that are relevant to GDPs, many of which are related to arrival demand. In particular, the total amount of arrival demand may be uncertain (popups, flight cancellations) or simply the distribution of demand over time (drift). Not only are there opportunities to research the nature of these uncertainties, but also how they should be incorporated into the planning of a GDP. For example, flight cancellations can be due to external factors, such as weather elsewhere in the NAS, or as the response of an air carrier to a GDP. Popups raise even more conflicting questions regarding the equity of a program to participants, as the exemption status of a flight can depend on when the flight plan[53] is filed.

Costing and Equity

A second area of future research would be to improve the cost functions used by the tool to calculate ground, air, and general delay costs. These cost functions represent the relative cost of different types of delay to different aircraft and can be used to compare programs that allocate delay differently. In academic research, airborne delay is often multiplied by a constant factor between 1.2 and 3.0 to indicate that this type of delay is more costly than ground delay. However, as discussed previously[54], the delay cost relationship depends on factors inherent to an individual flight, such as the size and type of the aircraft and duration of airborne delay. Additional research should be conducted to explore not only the type of cost functions that would be appropriate for different aircraft, but also how the overall cost of a proposed program depends on these cost functions.

[53] Or other notice of intent to file a flight plan

[54] Please refer to §2.2.1, §2.3.3, §3.3.2, §4.2.5, and §4.5.1

Cost functions can also be used to control the distribution of delay among different aircraft. For example, assigning one hour of delay to a single flight is usually less desirable than assigning ten minutes each to six flights because of the increasing marginal cost of delay to individual aircraft. Furthermore, the equity of the decision could be questioned: even if a proposed GDP reduces the total amount of delay, is it fair to the single aircraft to bear the burden of all of the delay? On the surface, the answer is no, that all aircraft should be treated equally. Yet, such disparities of assigned delay often result when the TM waits for a more reliable weather forecast and most flights depart. The implication of equity is further complicated by fact that airlines control groups of flights. Future research could explore not only the notion of equity for individual flights and commercial carriers, but also the question of whether and to what extent the FAA should even be concerned with equity.

Provision of Information to Commercial Airlines

A third area of future research could be to explore the relationship between the FAA and operators. In practice, air carriers react to GDPs and inclement weather by revising their schedules, a procedure that is also highly time- and information-sensitive. Through a formalized process called Collaborative Decision Making (§2.1.2), the FAA also works in conjunction with participating airlines (and some GA carriers) to reschedule flights and reassign ground delays required by a GDP to reduce the cost of delays to the airlines. The role of CDM and its implications for planning GDPs is another area in which research could be conducted.

Furthermore, the current practice of decision-making for airlines is based on the deterministic information currently used to design a GDP. However, as Chapter Three of this thesis has shown, including uncertainty allows for a wealth of information to be provided to the traffic manager regarding a program. In the same vein, future research could look at the type of information that would benefit commercial airlines, for example, the likelihood that an existing GDP will be cancelled or be changed to a ground stop.

Advanced Uses of the Tool

A fourth area that could be explored by future research would be to expand the usage of the tool. While this thesis lists a variety of metrics that could be used to evaluate a GDP, additional research could design new metrics and explore the application of the tool to a GDP. For example, metrics such as queue size, total delay cost, and H3 can be used to compare different alternatives, but they can also be used as objective measures. If a proposed program runs the risk of a substantial airborne queue, does that make the program untenable? Furthermore, the iterative nature of the two-stage model allows the tool to be applied to a tree of arrival forecast scenarios. Research could be conducted to explore not only how these analyses could be conducted, but also how a multi-stage analysis compares with the eventual performance of the actual GDP and subsequent revisions.

Section 5.2.2: The Creation of Optimal GDPs

With an understanding of how to evaluate a proposed program, it will also be possible to suggest a GDP to the traffic manager that meets given criteria. An area of research that has received attention in the past has been the use of mathematical optimization to design GDPs. In §2.3.2, several stochastic optimization models were discussed, which use probabilistic tree-based arrival capacity profiles to capture the evolution of capacity uncertainty over time. These optimization models, however, include only a fraction of the considerations made by the traffic manager when proposing a GDP. There is tremendous opportunity to improve the use of optimization methods in the design of a GDP by improving the models.

GDP Models

First, optimization models relating to a GDP could be improved to account for considerations of safety, equity, or other costs, as discussed above and also in Chapter Two. For example, although delay can be aggregated into a single cost metric, research could explore the use of additional constraints to prevent the worst-case queue size from exceeding safety thresholds. Additionally, the sensitivity of "optimal" solutions to considerations of safety and equity could be made, either through hard constraints, probabilistic chance constraints, or by iterative analyses. The metrics discussed in this tool can be used to evaluate not only GDPs that are proposed by TMs, but also those from mathematical algorithms, as well.

NAS Models

Furthermore, while most recent models have focused on the single airport ground holding problem (SAGHP), research could be expanded to consider a wider system. First, research could explore the application of GDPs to multiple airports, and investigate whether there is sufficient interaction between separate programs to create a benefit to the FAA, or even to a single, large commercial carrier, by examining multiple GDPs simultaneously.

Second, and of greater concern to the SAGHP, en route congestion can also be modeled mathematically. Research could be conducted to explore the modeling of dynamic and stochastic en route congestion in the NAS and how this congestion impacts the performance of a GDP (and vice versa). Combined models could seek to identify aircraft with routes that are likely to cause congestion at both an airport and en route sectors. Ultimately, it may be possible to create a single GDP – or a single flow model – that could optimize the flow of aircraft through the NAS during periods of inclement weather.

Section 5.3: Use of this thesis

It is the hope of the author that this thesis will encourage the development of stochastic tools for managing traffic in the NAS. From the perspective of the FAA, the various exhibits in Chapter Three illustrate metrics that could be calculated given existing flight information and probabilistic capacity forecasts. For the airlines, this thesis opens up the possibility of further collaboration with the FAA and for requesting in the future new information that could be made available to assist with commercial air service planning. And for meteorological researchers, this thesis suggests the importance and utility of stochastic arrival capacity forecasts for the nation's airports.

Air travel in the U.S. is now safer than ever, despite a tremendous rise in demand. As we look to the future, it is this demand for air travel – and the resulting congestion – as well as rising energy prices that will put pressure on the FAA to not only administer the use of the NAS, but to ensure that it is used efficiently. Ground delay programs were created with such a goal in mind, that aircraft could be delayed in safety and without spending additional fuel. Yet, under current planning methods, Traffic Managers cannot fully assess the ultimate impact of a proposed GDP on the performance of the system, especially when the future arrival capacity of an airport is uncertain. In the future, as new technology improves the information that could be made available to traffic managers, uncertainty in arrival capacity can be incorporated into the GDP design process. Improvements in the process by which GDPs are designed could lead to safer skies, whereby traffic managers can anticipate airborne congestion with enough time to prevent it. Improvements in the process could also lead to a more efficient air transportation system, saving fuel and time for the air carriers and their passengers. This thesis provides examples of directions to pursue in working toward such a possible improvement.

Appendices and Supplemental Information

TABLE OF APPENDICES

Appendix 1A: ETMS Flight Data used in the Tool

ID: Record ID
Period: Time Period of Arrival (DD/HHMM) in 15-minute periods
ACID: Aircraft ID
TYPE: Type of aircraft
ORIG: Airport Code of Flight Departure Airport
ETD: Estimated Time of Departure
ETA: Estimated Time of Arrival

ID	Period	ACID	TYPE	ORIG	ETD	ETA
001	22/1500	53A1186	B735	MSY	A1237	E1500
002	22/1500	53A111	B752	BDL	A1236	E1502
003	22/1500	10A305	CRJ2	ORF	A1304	E1502
004	22/1500	47A126	DC93	MSP	A1403	E1502
005	22/1500	53A529	A319	BOS	A1216	E1504
006	22/1500	01A829	MD82	BDL	A1230	E1504
007	22/1500	01A311	MD83	LGA	A1252	E1504
008	22/1500	10A321	CRJ2	RDU	A1319	E1504
009	22/1500	01A548	MD82	TUL	A1335	E1505
010	22/1500	27A310	B733	AEX	A1303	E1507
011	22/1500	50A6808	CRJ2	MBS	A1408	E1507
012	22/1500	53A379	B733	CLT	A1336	E1508
013	22/1500	10A749	CRJ2	HPN	A1302	E1509
014	22/1500	20A1746	B738	IAH	A1307	E1510
015	22/1500	28A963	CRJ7	LIT	A1342	E1510
016	22/1500	20A1175	B735	EWR	A1301	E1511
017	22/1500	01A643	MD82	BOS	A1247	E1512
018	22/1500	10A803	CRJ2	ABE	A1334	E1512
019	22/1500	53A945	B772	EDDF	A0643	E1513
020	22/1500	48A46	B744	ATL	A1351	E1514
021	22/1515	53A433	B733	PVD	A1255	E1516
022	22/1515	01A2328	MD83	DFW	A1322	E1516
023	22/1515	01A378	MD82	SLC	A1240	E1517
024	22/1515	40A8011	E145	BTV	A1309	E1519
025	22/1515	53A8178	B752	LGA	A1323	E1520
026	22/1515	10A619	CRJ2	MKE	P1501	E1520
027	22/1515	10A617	CRJ2	MKE	P1501	E1520
028	22/1515	47A936	DC93	MEM	A1401	E1521
029	22/1515	28A415	CRJ7	HPN	A1326	E1525
030	22/1515	53A147	B752	IAD	A1357	E1526
031	22/1515	10A329	BA46	BUF	A1400	E1526
032	22/1515	10A376	CRJ2	SBN	P1501	E1527
033	22/1515	53A1225	B733	MIA	A1244	E1528
034	22/1515	01A718	MD82	DEN	A1329	E1528
035	22/1515	53A1105	A320	CYYZ	A1410	E1528
036	22/1515	40A8083	E145	MDT	A1356	E1529
037	22/1515	10A550	CRJ2	MSN	P1501	E1529
038	22/1515	28A926	E145	MLI	P1501	E1529
039	22/1530	38A037	B772	RKSI	E0315	E1530
040	22/1530	53A207	B735	MHT	A1312	E1530
041	22/1530	01A313	MD82	LGA	A1333	E1531
042	22/1530	53A8141	B752	BOS	A1317	E1533
043	22/1530	54A111	B733	CLT	A1401	E1534
044	22/1530	28A220	E145	GRB	P1501	E1534
045	22/1530	10A638	BA46	MLI	P1501	E1534
046	22/1530	01A1196	MD82	SAT	A1316	E1535
047	22/1530	34A1156	CRJ2	IAD	A1401	E1535
048	22/1530	01A1475	B752	MIA	A1251	E1536
049	22/1530	01A2276	MD83	AUS	A1325	E1537
050	22/1530	01A1555	MD83	PVD	A1327	E1537
051	22/1530	53A609	B752	DCA	A1408	E1537
052	22/1530	10A477	CRJ2	FWA	P1501	E1538
053	22/1530	28A404	E145	FWA	P1505	E1538
054	22/1530	53A1479	A320	FLL	A1252	E1540
055	22/1530	10A794	CRJ2	SPI	P1501	E1540
056	22/1530	28A377	E145	PIA	P1512	E1540
057	22/1530	28A120	E145	MSN	P1515	E1540
058	22/1530	01A1335	MD82	DTW	P1502	E1541
059	22/1530	10A621	CRJ2	MKE	P1521	E1541
060	22/1530	10A915	CRJ2	LAN	P1501	E1542
061	22/1530	18A7791	E145	IND	P1501	E1543
062	22/1530	28A303	E145	AZO	P1515	E1543
063	22/1530	10A727	CRJ2	ALB	A1347	E1544
064	22/1545	10A448	CRJ2	CYOW	A1401	E1546
065	22/1545	01A1672	MD83	IAH	A1329	E1547
066	22/1545	53A395	A320	BWI	A1409	E1547
067	22/1545	50A6967	CRJ2	TYS	A1430	E1547
068	22/1545	01A595	MD82	IND	P1505	E1547
069	22/1545	53A1595	A320	TPA	A1323	E1548
070	22/1545	53A534	B733	DEN	A1347	E1548

Figure A1A-1 (1 of 5): ETMS flight data used in the tool

ID	Period	ACID	TYPE	ORIG	ETD	ETA
071	22/1545	53A8173	B752	PHL	A1409	E1548
072	22/1545	01A4U	MD82	MSP	P1501	E1548
073	22/1545	53A330	B735	STL	P1509	E1548
074	22/1545	10A427	CRJ2	SYR	A1412	E1552
075	22/1545	53A8124	A320	IAD	A1420	E1552
076	22/1545	10A425	CRJ2	CVG	P1501	E1552
077	22/1545	53A407	B752	DTW	T1507	E1552
078	22/1545	01A2332	MD82	DFW	A1408	E1553
079	22/1545	01A1311	MD82	CYYZ	A1444	E1553
080	22/1545	10A362	CRJ2	TVC	P1501	E1553
081	22/1545	54A1825	E170	DCA	A1421	E1554
082	22/1545	28A160	E145	CMH	P1501	E1554
083	22/1545	50A6985	CRJ7	CMH	P1501	E1554
084	22/1545	18A7779	E145	SDF	P1459	E1555
085	22/1545	53A1145	A319	CLE	P1501	E1556
086	22/1545	01A1645	MD83	STL	P1514	E1556
087	22/1545	28A373	E145	CMI	P1525	E1556
088	22/1545	18A7751	E170	IND	P1515	E1557
089	22/1545	10A643	BA46	GRR	P1523	E1557
090	22/1545	28A338	E135	DBQ	P1527	E1557
091	22/1545	10A355	CRJ2	RIC	A1407	E1558
092	22/1545	01A730	MD83	MCI	P1501	E1558
093	22/1600	53A553	B733	ATL	A1426	E1600
094	22/1600	28A227	E145	DSM	P1511	E1600
095	22/1600	03A517	A319	CYUL	A1406	E1601
096	22/1600	50A6974	CRJ7	AUS	A1352	E1603
097	22/1600	28A257	E145	CLE	P1501	E1604
098	22/1600	24A1632	MD80	ATL	A1433	E1605
099	22/1600	01A1919	MD83	RDU	A1423	E1607
100	22/1600	28A228	E145	CID	P1529	E1607
101	22/1600	53A675	B733	LGA	A1408	E1608
102	22/1600	01A577	MD82	BWI	A1431	E1609
103	22/1600	10A357	BA46	SDF	P1512	E1609
104	22/1600	28A212	E145	IND	P1531	E1609
105	22/1600	26A436	A319	EDDL	A0713	E1610
106	22/1600	01A1421	MD82	BOS	A1352	E1610
107	22/1600	28A356	E145	GRR	P1542	E1611
108	22/1600	28A150	E135	TYS	A1456	E1612
109	22/1600	53A8150	B752	EWR	A1422	E1613
110	22/1600	28A851	E145	XNA	E1450	E1614
111	22/1615	50A6916	CRJ7	COS	A1415	E1616
112	22/1615	53A477	A319	PIT	T1510	E1616
113	22/1615	50A6792	CRJ2	BNA	A1457	E1617
114	22/1615	01A317	MD82	LGA	A1423	E1621
115	22/1615	28A923	E135	MSN	P1557	E1621

ID	Period	ACID	TYPE	ORIG	ETD	ETA
116	22/1615	28A229	E135	ALB	A1422	E1622
117	22/1615	28A972	CRJ7	MKE	P1605	E1622
118	22/1615	28A263	E145	HSV	P1500	E1624
119	22/1615	18A7741	E170	DSM	P1531	E1624
120	22/1615	01A1342	B752	STL	P1540	E1625
121	22/1615	53A1294	B735	MSP	P1536	E1626
122	22/1615	28A287	E145	SDF	P1529	E1627
123	22/1615	48A64	B741	ATL	S1459	E1628
124	22/1615	10A345	CRJ2	ROC	P1501	E1628
125	22/1615	28A865	CRJ7	BNA	P1523	E1628
126	22/1615	53A533	B752	BOS	A1418	E1629
127	22/1615	18A7752	E170	IAH	A1424	E1629
128	22/1615	01A2325	MD83	EWR	A1442	E1629
129	22/1630	53A1598	A320	LAS	A1334	E1631
130	22/1630	01A1224	MD82	ELP	A1402	E1631
131	22/1630	14A2210	E45X	IAH	A1427	E1631
132	22/1630	28A443	CRJ7	ATL	P1506	E1632
133	22/1630	10A635	CRJ2	LEX	P1522	E1632
134	22/1630	12A295	B772	EGLL	E0844	E1635
135	22/1630	53A1208	B733	TUS	A1339	E1635
136	22/1630	01A1049	MD82	MSY	A1430	E1635
137	22/1630	01A1061	MD82	PHL	P1500	E1636
138	22/1630	50A6976	CRJ7	CYEG	A1341	E1637
139	22/1630	18A7811	E145	IND	P1555	E1637
140	22/1630	28A366	E135	RST	P1555	E1638
141	22/1630	01A1840	B752	RNO	A1327	E1639
142	22/1630	01A1476	MD82	PHX	A1347	E1639
143	22/1630	28A260	E145	MEM	P1521	E1639
144	22/1630	28A151	E145	BUF	P1521	E1639
145	22/1630	28A104	E145	EVV	P1540	E1639
146	22/1630	28A326	E145	CVG	P1549	E1639
147	22/1630	01A862	MD82	ABQ	A1418	E1640
148	22/1630	18A7758	E170	ABQ	A1419	E1641
149	22/1630	28A362	E145	GSP	P1506	E1641
150	22/1630	01A1167	MD82	BDL	A1430	E1642
151	22/1630	28A136	E145	IAD	P1508	E1642
152	22/1630	01A644	MD82	MCI	P1540	E1642
153	22/1645	16A9016	B742	JFK	P1456	E1645
154	22/1645	28A253	E145	TVC	P1554	E1645
155	22/1645	28A996	E145	PIA	P1617	E1645
156	22/1645	01A1547	MD82	BOS	A1434	E1646
157	22/1645	20A1171	B735	EWR	A1458	E1646
158	22/1645	53A682	B752	SEA	A1320	E1648
159	22/1645	21A463	CRJ2	CVG	P1557	E1648
160	22/1645	28A313	CRJ7	DAY	P1605	E1648

Figure A1A-1 (2 of 5): ETMS flight data used in the tool

ID	Period	ACID	TYPE	ORIG	ETD	ETA
161	22/1645	50A6872	CRJ7	DAY	P1605	E1648
162	22/1645	53A350	A320	PDX	A1317	E1650
163	22/1645	53A1532	A320	PHX	A1408	E1651
164	22/1645	28A959	CRJ7	LIT	P1536	E1651
165	22/1645	53A1210	B733	DFW	T1503	E1652
166	22/1645	53A884	B772	RJAA	A0543	E1655
167	22/1645	28A898	E135	RIC	P1511	E1655
168	22/1645	10A848	CRJ2	FSD	P1543	E1656
169	22/1645	28A203	E145	OMA	P1548	E1656
170	22/1645	50A6962	CRJ2	SGF	S1558	E1656
171	22/1645	01A370	MD82	MSP	P1604	E1656
172	22/1645	53A1114	B733	CYYC	A1356	E1657
173	22/1645	10A548	BA46	MSN	S1630	E1657
174	22/1645	53A8172	B772	DEN	T1510	E1658
175	22/1645	28A103	E145	CLT	P1513	E1658
176	22/1645	53A611	A320	DCA	P1528	E1659
177	22/1700	10A828	CRJ1	BMI	S1629	E1700
178	22/1700	01A2018	MD83	SFO	A1314	E1701
179	22/1700	01A1580	MD83	SAN	A1339	E1701
180	22/1700	53A100	B763	LAX	A1343	E1702
181	22/1700	53A300	A319	SMF	A1337	E1703
182	22/1700	53A468	B752	SAN	A1351	E1703
183	22/1700	01A2336	MD82	DFW	P1517	E1703
184	22/1700	53A242	B733	MCI	P1603	E1703
185	22/1700	53A1214	A319	OAK	A1332	E1704
186	22/1700	01A1002	MD82	TUS	A1414	E1705
187	22/1700	53A404	B733	SLC	A1422	E1705
188	22/1700	40A7980	E145	STL	S1618	E1705
189	22/1700	10A801	CRJ1	GRB	S1627	E1705
190	22/1700	24A1660	MD90	SLC	A1426	E1707
191	22/1700	01A321	MD83	LGA	P1521	E1707
192	22/1700	50A6817	CRJ2	MEM	P1554	E1707
193	22/1700	01A1514	MD82	LAX	A1347	E1710
194	22/1700	53A677	A320	LGA	T1519	E1710
195	22/1700	10A593	BA46	MLI	S1639	E1710
196	22/1700	54A924	B733	PHL	P1530	E1712
197	22/1700	26A430	B744	EDDF	A0832	E1713
198	22/1700	53A1292	B733	GEG	A1401	E1713
199	22/1700	53A1200	B735	BOI	A1411	E1713
200	22/1715	39A611	B744	EHAM	A0903	E1715
201	22/1715	43A3628	BA46	MSP	S1616	E1715
202	22/1715	53A132	B763	SFO	A1348	E1716
203	22/1715	53A570	B752	SNA	A1406	E1716
204	22/1715	10A568	CRJ2	TUL	P1546	E1716
205	22/1715	01A1284	MD82	DCA	P1552	E1716
206	22/1715	10A835	CRJ1	CWA	S1630	E1716
207	22/1715	40A8061	E145	SBN	S1651	E1716
208	22/1715	10A905	CRJ2	ICT	P1549	E1717
209	22/1715	01A1076	MD82	TUL	P1600	E1717
210	22/1715	28A934	E145	SGF	P1612	E1717
211	22/1715	47A1239	DC94	DTW	P1634	E1717
212	22/1715	01A499	MD82	DCA	P1551	E1719
213	22/1715	53A1164	B735	OMA	P1603	E1719
214	22/1715	28A318	E145	CMI	S1648	E1719
215	22/1715	50A6825	CRJ2	PIA	S1637	E1720
216	22/1715	53A648	A319	SJC	A1343	E1721
217	22/1715	49A945	A333	ESSA	E0832	E1722
218	22/1715	28A190	CRJ7	CMH	S1627	E1722
219	22/1715	10A744	CRJ1	CID	S1638	E1722
220	22/1715	46A908	MD83	MCO	A1458	E1724
221	22/1715	01A844	MD83	SJC	A1337	E1726
222	22/1715	01A1556	B752	SNA	A1416	E1726
223	22/1715	10A309	CRJ2	PWM	P1506	E1726
224	22/1715	01A2146	B752	TJSJ	A1300	E1727
225	22/1715	44A810	A320	MMGL	E1348	E1727
226	22/1715	53A615	B733	DCA	P1555	E1727
227	22/1715	09A1	A320	PHX	A1444	E1728
228	22/1715	10A702	CRJ2	OKC	P1550	E1728
229	22/1715	03A505	A319	CYYZ	S1616	E1728
230	22/1715	40A7972	E145	BTV	P1532	E1729
231	22/1730	28A270	E135	ORF	S1541	E1735
232	22/1730	28A916	CRJ7	ICT	P1616	E1735
233	22/1730	10A433	CARJ	CMH	S1642	E1736
234	22/1730	01A1301	MD82	PHL	P1552	E1737
235	22/1730	24A908	MD80	ATL	S1601	E1737
236	22/1730	28A202	E145	LSE	S1645	E1737
237	22/1730	28A421	E145	IND	S1657	E1737
238	22/1730	08A7138	CRJ2	BNA	P1631	E1738
239	22/1730	28A164	E145	PIT	P1627	E1739
240	22/1730	01A1375	MD82	EWR	P1554	E1740
241	22/1730	10A507	BA46	ATW	P1705	E1740
242	22/1730	53A909	B763	EHAM	A0918	E1741
243	22/1730	28A439	CRJ7	CYUL	P1547	E1742
244	22/1745	21A464	CRJ	CVG	S1654	E1745
245	22/1745	01A1623	MD80	DTW	S1655	E1746
246	22/1745	28A116	E145	OKC	P1610	E1748
247	22/1745	28A236	E145	CLE	S1647	E1748
248	22/1745	14A2608	E135	CLE	S1655	E1748
249	22/1745	01A1450	MD82	RSW	P1528	E1749
250	22/1745	01A87	B772	EGLL	E0953	E1750

Figure A1A-1 (3 of 5): ETMS flight data used in the tool

ID	Period	ACID	TYPE	ORIG	ETD	ETA
251	22/1745	50A6969	CRJ2	IND	S1654	E1750
252	22/1745	28A243	CRJ7	DSM	S1657	E1751
253	22/1745	28A124	E135	EVV	S1655	E1752
254	22/1745	28A255	E145	GRB	S1715	E1752
255	22/1745	28A953	E145	MSN	S1723	E1752
256	22/1745	53A719	A319	PVD	P1542	E1753
257	22/1745	53A633	B735	BDL	P1547	E1753
258	22/1745	01A2013	MD82	MCO	P1543	E1755
259	22/1745	50A6860	CRJ2	SYR	S1625	E1756
260	22/1745	18A7740	E170	ROC	S1636	E1759
261	22/1800	01A55	B763	EGCC	A0952	E1800
262	22/1800	10A471	CRJ1	RDU	S1614	E1800
263	22/1800	53A1144	A319	CYVR	A1416	E1801
264	22/1800	01A2340	MD83	DFW	P1616	E1801
265	22/1800	53A455	A319	PHL	P1618	E1801
266	22/1800	10A429	CRJ2	SAV	P1600	E1802
267	22/1800	08A7202	CRJ7	CLE	S1652	E1802
268	22/1800	01A89	B763	EBBR	E0918	E1803
269	22/1800	53A929	B772	EGLL	A0952	E1803
270	22/1800	44A800	A318	MMMX	A1418	E1803
271	22/1800	53A315	B733	MHT	P1552	E1803
272	22/1800	44A808	A320	MMMY	S1510	E1804
273	22/1800	20A1646	B733	IAH	P1601	E1805
274	22/1800	10A393	CARJ	CAK	S1704	E1805
275	22/1800	50A6876	CRJ2	FWA	S1720	E1805
276	22/1800	28A128	E145	RIC	P1622	E1806
277	22/1800	53A1495	A320	MCO	P1548	E1807
278	22/1800	28A265	E145	MDT	S1627	E1807
279	22/1800	28A348	CRJ7	XNA	S1644	E1807
280	22/1800	01A325	MD82	LGA	P1620	E1809
281	22/1800	50A6827	CRJ2	AZO	S1726	E1810
282	22/1800	53A923	A320	IAD	P1644	E1812
283	22/1800	01A1803	MD82	BOS	P1602	E1814
284	22/1815	46A436	MD83	FLL	P1517	E1816
285	22/1815	53A679	B735	LGA	P1620	E1816
286	22/1815	53A645	B752	EWR	P1628	E1816
287	22/1815	01A1173	MD82	FLL	P1547	E1818
288	22/1815	50A6843	CRJ2	ROA	S1636	E1818
289	22/1815	11A626	B762	LIMC	S0850	E1819
290	22/1815	50A6820	CRJ2	BHM	S1627	E1819
291	22/1815	53A244	B772	DEN	P1635	E1819
292	22/1815	28A224	E145	SYR	S1641	E1819
293	22/1815	18A7746	E170	BUF	S1703	E1819
294	22/1815	10A307	CRJ1	CLT	S1638	E1820
295	22/1815	01A1898	MD80	STL	S1730	E1820
296	22/1815	01A1836	MD82	PHX	S1539	E1821
297	22/1815	28A300	E135	CYOW	S1635	E1821
298	22/1815	28A290	CRJ7	BNA	S1706	E1821
299	22/1815	53A531	B733	BOS	P1608	E1823
300	22/1815	53A487	B733	BWI	P1647	E1823
301	22/1815	53A385	A320	PIT	S1713	E1823
302	22/1815	10A792	CRJ1	SPI	S1744	E1823
303	22/1815	01A2326	MD83	PSP	P1518	E1824
304	22/1815	13A705	A332	EGCC	A1026	E1825
305	22/1815	01A400	MD83	SAN	P1507	E1825
306	22/1815	53A617	B733	DCA	P1655	E1827
307	22/1815	10A751	CRJ1	HPN	S1629	E1828
308	22/1815	40A8028	E145	RIC	S1648	E1829
309	22/1830	01A1712	B752	LAS	P1544	E1830
310	22/1830	53A525	B733	BOS	P1614	E1830
311	22/1830	10A729	CRJ1	ALB	S1637	E1830
312	22/1830	53A104	B752	LAX	P1518	E1831
313	22/1830	10A742	CRJ1	GSO	S1654	E1832
314	22/1830	53A1204	A319	MSP	P1742	E1832
315	22/1830	17A508	B732	MMMY	S1540	E1833
316	22/1830	28A901	E145	MSP	S1745	E1836
317	22/1830	53A787	B733	GRR	S1802	E1836
318	22/1830	08A7038	CRJ7	ATL	S1655	E1837
319	22/1830	10A511	BA46	CVG	S1746	E1837
320	22/1830	28A294	E145	FWA	S1801	E1840
321	22/1830	54A331	B73F	PHL	S1649	E1841
322	22/1830	03A529	CRJ1	CYOW	S1656	E1841
323	22/1830	01A2088	MD83	SEA	P1509	E1843
324	22/1830	10A576	CRJ1	MSN	S1815	E1843
325	22/1830	28A254	E135	DBQ	S1818	E1843
326	22/1830	28A967	E145	CID	S1806	E1844
327	22/1830	10A468	CRJ1	SBN	S1818	E1844
328	22/1845	18A7759	E170	MSY	S1639	E1845
329	22/1845	28A988	E135	RST	S1802	E1845
330	22/1845	28A142	E145	AZO	S1818	E1846
331	22/1845	28A946	E145	BMI	S1817	E1848
332	22/1845	28A268	E145	PIA	S1819	E1848
333	22/1845	10A929	CRJ1	CHS	S1650	E1849
334	22/1845	18A7756	E170	MSY	S1644	E1850
335	22/1845	28A417	CRJ7	HPN	S1655	E1850
336	22/1845	08A7018	CRJ2	GSP	S1700	E1851
337	22/1845	18A7789	E145	SDF	S1753	E1851
338	22/1845	10A607	CRJ1	DAY	S1802	E1851
339	22/1845	53A500	B752	SAN	P1545	E1852
340	22/1845	08A7020	CRJ2	CAE	S1645	E1852

Figure A1A-1 (4 of 5): ETMS flight data used in the tool

ID	Period	ACID	TYPE	ORIG	ETD	ETA
431	22/1945	24A392	B732	CVG	S1856	E1946
432	22/1945	18A7821	E145	IND	S1903	E1946
433	22/1945	32A573	A320	MKJS	P1605	E1947
434	22/1945	28A183	E145	SWF	S1751	E1947
435	22/1945	10A394	CRJ1	TYS	S1827	E1947
436	22/1945	48A128	B742	ANC	A1446	E1949
437	22/1945	50A6882	CRJ2	FSD	S1822	E1951
438	22/1945	28A405	E145	TYS	S1834	E1951
439	22/1945	28A165	E145	PIT	S1842	E1951
440	22/1945	54A746	B733	CLT	S1812	E1953
441	22/1945	50A6978	CRJ7	IAH	S1743	E1954
442	22/1945	50A6823	CRJ2	SGF	S1828	E1954
443	22/1945	53A246	B733	OMA	S1843	E1955
444	22/1945	01A1775	MD83	TPA	P1747	E1956
445	22/1945	53A1246	B735	STL	S1908	E1956
446	22/1945	28A920	E145	ICT	S1829	E1957
447	22/1945	53A920	E145	ICT	S1829	E1957
448	22/1945	40A8063	E145	ORF	S1809	E1958
449	22/2000	40A8055	E145	RIC	S1819	E2000
450	22/2000	53A1161	B735	MSP	S1903	E2000
451	22/2000	20A1189	B73J	EWR	S1806	E2004
452	22/2000	28A406	E145	CVG	S1913	E2004
453	22/2000	28A244	CRJ7	DSM	S1912	E2006
454	22/2000	28A239	E145	CID	S1926	E2006
455	22/2000	53A683	B752	LGA	S1813	E2007
456	22/2000	51A8	A332	LSZH	A1122	E2009
457	22/2000	01A509	MD80	BOS	S1748	E2009
458	22/2000	50A6870	CRJ2	FAR	S1829	E2009
459	22/2000	01A1281	MD80	PVD	S1756	E2010
460	22/2000	47A1241	DC9	DTW	S1919	E2011
461	22/2000	09A720	A320	LAS	P1713	E2012
462	22/2000	08A7123	CRJ2	RDU	S1809	E2013
463	22/2000	01A2348	MD80	DFW	S1817	E2013
464	22/2000	10A826	CRJ1	BMI	S1943	E2014
465	22/2015	01A111	B763	LIRF	A1026	E2015
466	22/2015	53A1535	A320	MCO	S1757	E2015
467	22/2015	53A643	B752	EWR	P1828	E2015
468	22/2015	47A251	A319	DTW	S1923	E2016
469	22/2015	50A6841	CRJ2	PIA	S1944	E2016
470	22/2015	12A297	B744	EGLL	E1220	E2017
471	22/2015	10A841	CRJ1	AZO	S1944	E2017
472	22/2015	53A1289	A319	CLT	P1846	E2018
473	22/2015	01A1371	MD80	CYYZ	S1900	E2018
474	22/2015	53A537	B752	BOS	S1809	E2020
475	22/2015	28A997	E135	BNA	S1905	E2020
476	22/2015	28A172	E145	EVV	S1924	E2020
477	22/2015	28A198	E145	GRB	S1942	E2021
478	22/2015	01A424	MD80	LAX	S1641	E2022
479	22/2015	01A1489	MD80	MCO	S1753	E2022
480	22/2015	10A424	CRJ1	CYOW	S1840	E2022
481	22/2015	53A281	B763	IAD	P1858	E2023
482	22/2015	14A2498	E135	CLE	S1924	E2023
483	22/2015	53A1109	B752	CYYZ	S1915	E2025
484	22/2015	01A1967	MD80	PHL	S1829	E2026
485	22/2015	04A050	A343	LFPG	E1116	E2028
486	22/2015	01A333	MD80	LGA	S1827	E2028
487	22/2015	53A621	A320	DCA	S1858	E2029

Figure A1A-1 (5 of 5): ETMS flight data used in the tool

Notes:

1. **ETMS data used in the tool is for all scheduled ORD flight arrivals on June 22, 2005 between 15:00 and 20:30 Z, as of 14:45 Z on June 22, 2005.**
2. **The data set exhibited here is the full set used for the tool and is part of a larger data sample from from ETMS**
3. **Air carrier codes in the ACID have been replaced by a three-character code (##A)**
4. **Please refer to §2.2.2 for more information regarding ETMS**
5. **Please refer to §3.1 for more information regarding the data used in the tool**

Appendix 1B: Origination Airports

Figure A1B-1 contains a list of all departure airports for flights in the data used by the tool.

Code: FAA or IATA airport designation code
Location: Geographic description of location of airport
Distance: Miles from ORD (by great circle)

Source #1: Airport Codes are from ETMA (see Appendix 1A)
Source #2: Location and distance are from the Great Circle Mapper: http://gc.kls2.com/, March 8, 2006

Code	Location	Distance
ABE	Allentown, PA, US	654 mi
ABQ	Albuquerque, NM, US	1118 mi
AEX	Alexandria, LA, US	778 mi
ALB	Albany, NY, US	723 mi
ANC	Anchorage, AK, US	2846 mi
ATL	Atlanta, GA, US	606 mi
ATW	Appleton, WI, US	160 mi
AUS	Austin, TX, US	978 mi
AZO	Kalamazoo, MI, US	122 mi
BDL	Windsor Locks, CT, US	783 mi
BHM	Birmingham, AL, US	584 mi
BMI	Bloomington/Normal, IL, US	116 mi
BNA	Nashville, TN, US	409 mi
BOI	Boise, ID, US	1437 mi
BOS	Boston, MA, US	867 mi
BTV	Burlington, VT, US	763 mi
BUF	Buffalo, NY, US	473 mi
BWI	Baltimore, MD, US	621 mi
CAE	Columbia, SC, US	666 mi
CAK	Akron, OH, US	343 mi
CHS	Charleston, SC, US	760 mi
CID	Cedar Rapids, IA, US	196 mi
CLE	Cleveland, OH, US	316 mi
CLT	Charlotte, NC, US	599 mi
CMH	Columbus, OH, US	296 mi
CMI	Champaign/Urbana, IL, US	135 mi
COS	Colorado Springs, CO, US	911 mi
CVG	Covington, KY, US	265 mi
CWA	Mosinee, WI, US	213 mi
CYEG	Edmonton, AB, CA	1419 mi

Figure A1B-1 (1 of 4): Airports included in the sample data set used in the tool

Code	Location	Distance
CYOW	Ottawa, ON, CA	655 mi
CYUL	Montréal, QC, CA	748 mi
CYVR	Vancouver, BC, CA	1764 mi
CYWG	Winnipeg, MB, CA	707 mi
CYYC	Calgary, AB, CA	1385 mi
CYYZ	Toronto, ON, CA	436 m
DAY	Dayton, OH, US	240 mi
DBQ	Dubuque, IA, US	147 mi
DCA	Washington, DC, US	612 mi
DEN	Denver, CO, US	888 mi
DFW	Dallas-Fort Worth, TX, US	802 mi
DSM	Des Moines, IA, US	299 mi
DTW	Detroit, MI, US	234 mi
EBBR	Brussels, BE	4159 mi
EDDF	Frankfurt, DE	4343 mi
EDDL	Duesseldorf (Düsseldorf), DE	4230 mi
EDDM	München (Munich), DE	4529 mi
EGCC	Manchester, England, GB	3826 mi
EGLL	London, England, GB	3953 mi
EHAM	Amsterdam, NL	4120 mi
ELP	El Paso, TX, US	1236 mi
ESSA	Stockholm, SE	4272 mi
EVV	Evansville, IN, US	273 mi
EWR	Newark, NJ, US	719 mi
FAR	Fargo, ND, US	557 mi
FLL	Fort Lauderdale, FL, US	1182 mi
FSD	Sioux Falls, SD, US	463 mi
FWA	Fort Wayne, IN, US	157 mi
GEG	Spokane, WA, US	1498 mi
GRB	Green Bay, WI, US	173 mi
GRR	Grand Rapids, MI, US	137 mi
GSO	Greensboro, NC, US	590 mi
GSP	Greer, SC, US	577 mi
HPN	White Plains, NY, US	738 mi
HSV	Huntsville, AL, US	510 mi
IAD	Washington, DC, US	589 mi
IAH	Houston, TX, US	925 mi
ICT	Wichita, KS, US	588 mi
IND	Indianapolis, IN, US	177 mi
JFK	New York, NY, US	740 mi

Figure A1B-1 (2 of 4): Airports included in the sample data set used in the tool

Code	Location	Distance
LAN	Lansing, MI, US	179 mi
LAS	Las Vegas, NV, US	1514 mi
LAX	Los Angeles, CA, US	1745 mi
LEMD	Madrid, ES	4201 mi
LEX	Lexington, KY, US	323 mi
LFPG	Paris, FR	4152 mi
LGA	New York, NY, US	733 mi
LIMC	Milano (Milan), IT	4523 mi
LIRF	Roma (Rome), IT	4823 mi
LIT	Little Rock, AR, US	552 mi
LNK	Lincoln, NE, US	466 mi
LSE	La Crosse, WI, US	215 mi
LSZH	Zürich, CH	4443 mi
LTBA	Istanbul, TR	5491 mi
MBS	Saginaw, MI, US	222 mi
MCI	Kansas City, MO, US	403 mi
MCO	Orlando, FL, US	1005 mi
MDT	Harrisburg, PA, US	594 mi
MEM	Memphis, TN, US	491 mi
MHT	Manchester, NH, US	843 mi
MIA	Miami, FL, US	1197 mi
MKE	Milwaukee, WI, US	67 mi
MKJS	Montego Bay, JM	1721 mi
MLI	Moline, IL, US	139 m
MMGL	Guadalajara, MX	1731 mi
MMMX	Ciudad de Mexico (Mexico City), MX	1686 mi
MMMY	Monterrey, MX	1315 mi
MMUN	Cancún, MX	1444 mi
MSN	Madison, WI, US	108 mi
MSP	Minneapolis, MN, US	334 mi
MSY	New Orleans, LA, US	837 mi
OAK	Oakland, CA, US	1836 mi
OKC	Oklahoma City, OK, US	693 mi
OMA	Omaha, NE, US	416 mi
ORF	Norfolk, VA, US	717 mi
PDX	Portland, OR, US	1739 mi
PHL	Philadelphia, PA, US	678 mi
PHX	Phoenix, AZ, US	1440 mi
PIA	Peoria, IL, US	130 mi
PIT	Pittsburgh, PA, US	412 mi

Figure A1B-1 (3 of 4): Airports included in the sample data set used in the tool

Code	Location	Distance
PSP	Palm Springs, CA, US	1652 mi
PVD	Providence, RI, US	849 mi
PWM	Portland, ME, US	900 mi
RDU	Raleigh/Durham, NC, US	646 mi
RIC	Richmond, VA, US	642 mi
RJAA	Tokyo (Narita), Honshu, JP	6274 mi
RKSI	Seoul, KR	6551 mi
RNO	Reno, NV, US	1671 mi
ROA	Roanoke, VA, US	531 mi
ROC	Rochester, NY, US	528 mi
RST	Rochester, MN, US	268 mi
RSW	Fort Myers, FL, US	1120 mi
SAN	San Diego, CA, US	1723 mi
SAT	San Antonio, TX, US	1042 mi
SAV	Savannah, GA, US	773 mi
SBN	South Bend, IN, US	84 mi
SDF	Louisville, KY, US	287 mi
SEA	Seattle, WA, US	1721 m
SFO	San Francisco, CA, US	1846 mi
SGF	Springfield, MO, US	438 mi
SJC	San Jose, CA, US	1829 mi
SLC	Salt Lake City, UT, US	1250 mi
SMF	Sacramento, CA, US	1781 mi
SNA	Santa Ana, CA, US	1726 mi
SPI	Springfield, IL, US	174 mi
STL	St. Louis, MO, US	258 mi
SWF	Newburgh, NY, US	713 mi
SYR	Syracuse, NY, US	607 mi
TJSJ	San Juan, PR, US	2072 mi
TOL	Toledo, OH, US	213 mi
TPA	Tampa, FL, US	1012 mi
TUL	Tulsa, OK, US	585 mi
TUS	Tucson, AZ, US	1437 mi
TVC	Traverse City, MI, US	224 mi
TYS	Knoxville, TN, US	475 mi
VHHH	Hong Kong, HK	7794 mi
XNA	Fayetteville/Springdale, AR, US	522 mi

Figure A1B-1 (4 of 4): Airports included in the sample data set used in the tool

Appendix 1C: Supplemental Figures for the Base Case (no GDP)

Chapter Three contains many representations of the performance of a GDP. Appendix 1C contains similar representations, except delay is shown for the case when there is no GDP. The following five figures are:

A1C-1: A table of airborne and ground delays by flight. Note that ground delay is not assigned to any flight.

A1C-2: A chart of airborne delay by flight and likelihood

A1C-3: A chart of the four-flight moving average comparison of airborne delay. Note that variability decreases when there is no GDP.

A1C-4: A chart of airport arrival demand and capacity by time period, which also includes the reference FAAR arrival rates for comparison. Note the impetus for the TM to act within the next half hour or risk airborne delays under FC #1.

A1C-5: A histogram of the cost of delays by flight

Flight Ground and Airborne Delays by Outcome

Flight ID	Ground Delay	Airborne Delay Exp	FC 1	FC 2	FC 3	FC 4	FC 5
53A1186	0:00	0:00	0:00	0:00	0:00	0:00	0:00
53A111	0:00	0:00	0:01	0:00	0:00	0:00	0:00
10A305	0:00	0:01	0:02	0:01	0:01	0:01	0:01
47A126	0:00	0:02	0:04	0:01	0:01	0:01	0:01
53A529	0:00	0:01	0:03	0:00	0:00	0:00	0:00
01A829	0:00	0:02	0:05	0:01	0:00	0:00	0:00
01A311	0:00	0:03	0:06	0:02	0:01	0:01	0:01
10A321	0:00	0:04	0:08	0:02	0:02	0:02	0:02
01A548	0:00	0:04	0:08	0:02	0:01	0:01	0:01
27A310	0:00	0:03	0:08	0:01	0:00	0:00	0:00
50A6808	0:00	0:04	0:09	0:02	0:00	0:00	0:00
53A379	0:00	0:03	0:09	0:01	0:00	0:00	0:00
10A749	0:00	0:03	0:09	0:01	0:00	0:00	0:00
20A1746	0:00	0:03	0:09	0:01	0:00	0:00	0:00
28A963	0:00	0:04	0:10	0:02	0:00	0:00	0:00
20A1175	0:00	0:04	0:10	0:01	0:00	0:00	0:00
01A643	0:00	0:04	0:10	0:01	0:00	0:00	0:00
10A803	0:00	0:05	0:11	0:02	0:00	0:00	0:00
53A945	0:00	0:05	0:11	0:02	0:00	0:00	0:00
48A46	0:00	0:04	0:11	0:01	0:00	0:00	0:00
...							

Time is expressed in hh:mm

Figure A1C-1: Sample of flight delays expected if no GDP is implemented

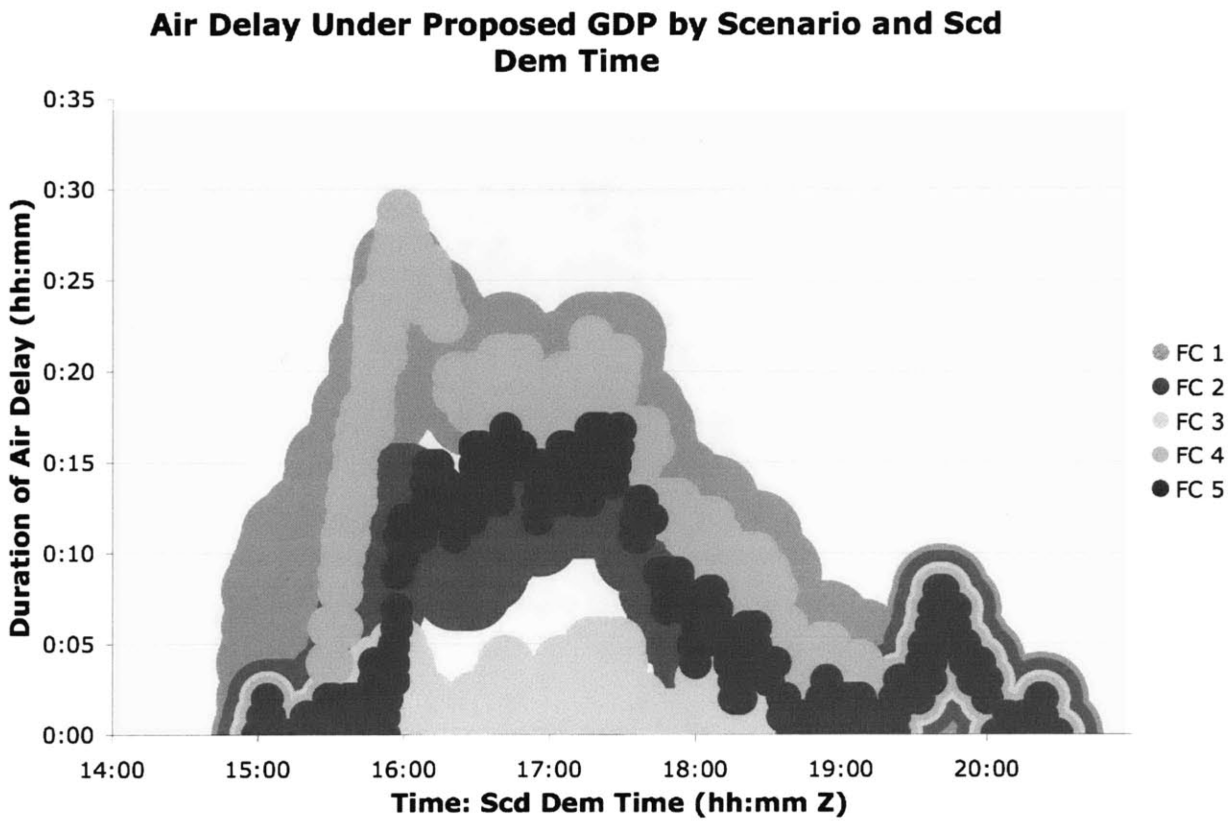


Figure A1C-2: Airborne (total) delays by flight and likelihood without GDP – see Fig. 3-21

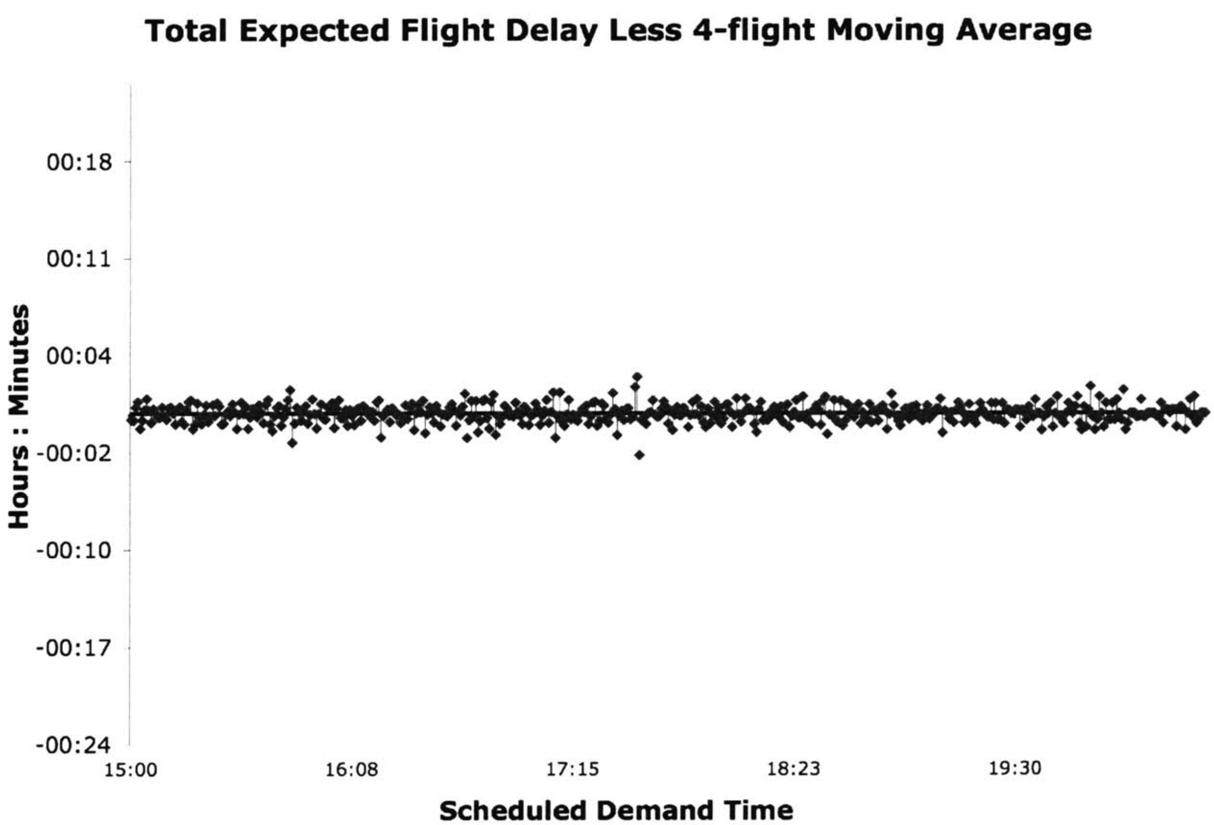


Figure A1C-3: Expected flight delays compared to the 4-flight moving average without GDP – see Fig. 3-36

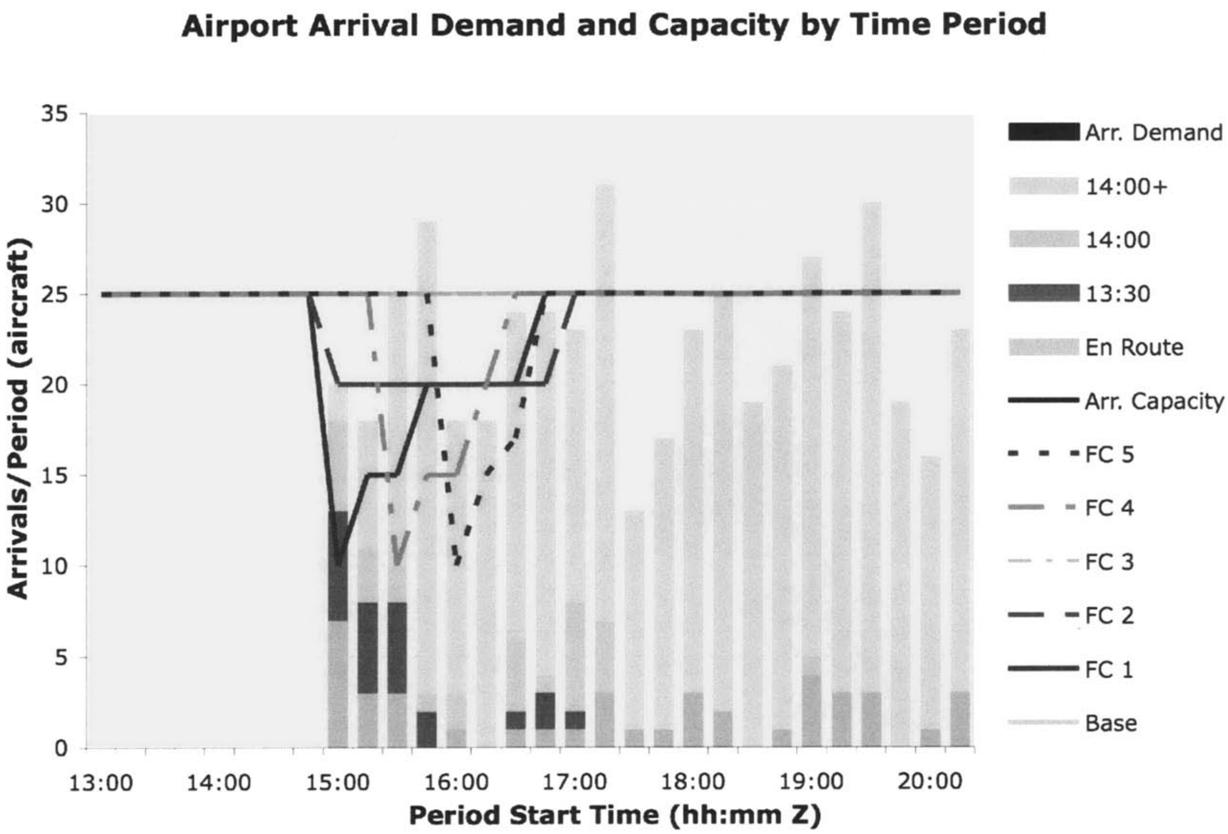


Figure A1C-4: Arrival capacity and demand (by departure time) profiles without GDP – see Fig. 3-27

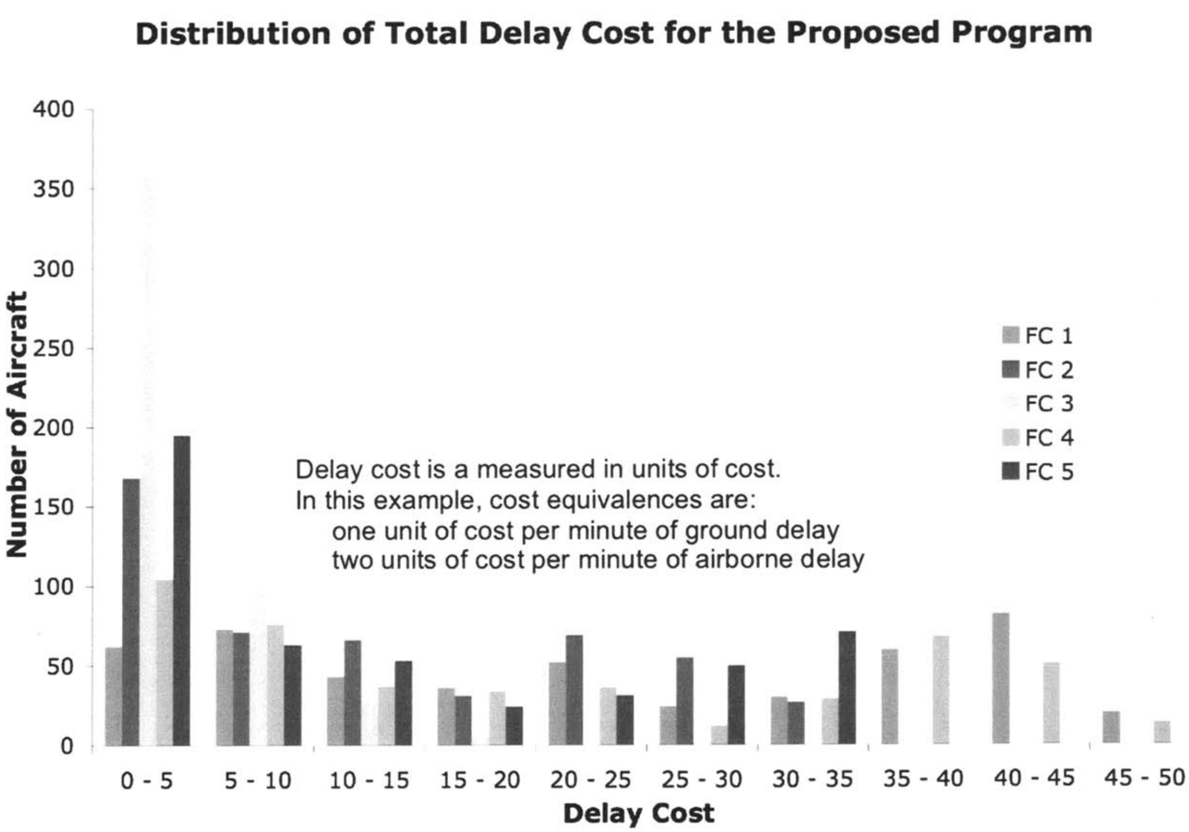


Figure A1C-5: Histogram of total delay cost distributions by flight and scenario without GDP – see Fig. 3-31

Appendix 1D: Supplemental Figures for the Two-Stage Model

Appendix 1D contains supplemental illustrations of results for the two-stage model detailed in §3.4.

A1D-1: A chart of the accumulation of ground delay over time. Note that delay is the same for all profiles until the GDP is revised.

A1D-2: A chart of arrival queues by time. Note that the maximum expected queue size dramatically decreases when the tool assumes that the GDP will be revised.

A1D-3: A histogram of delay cost by flight.

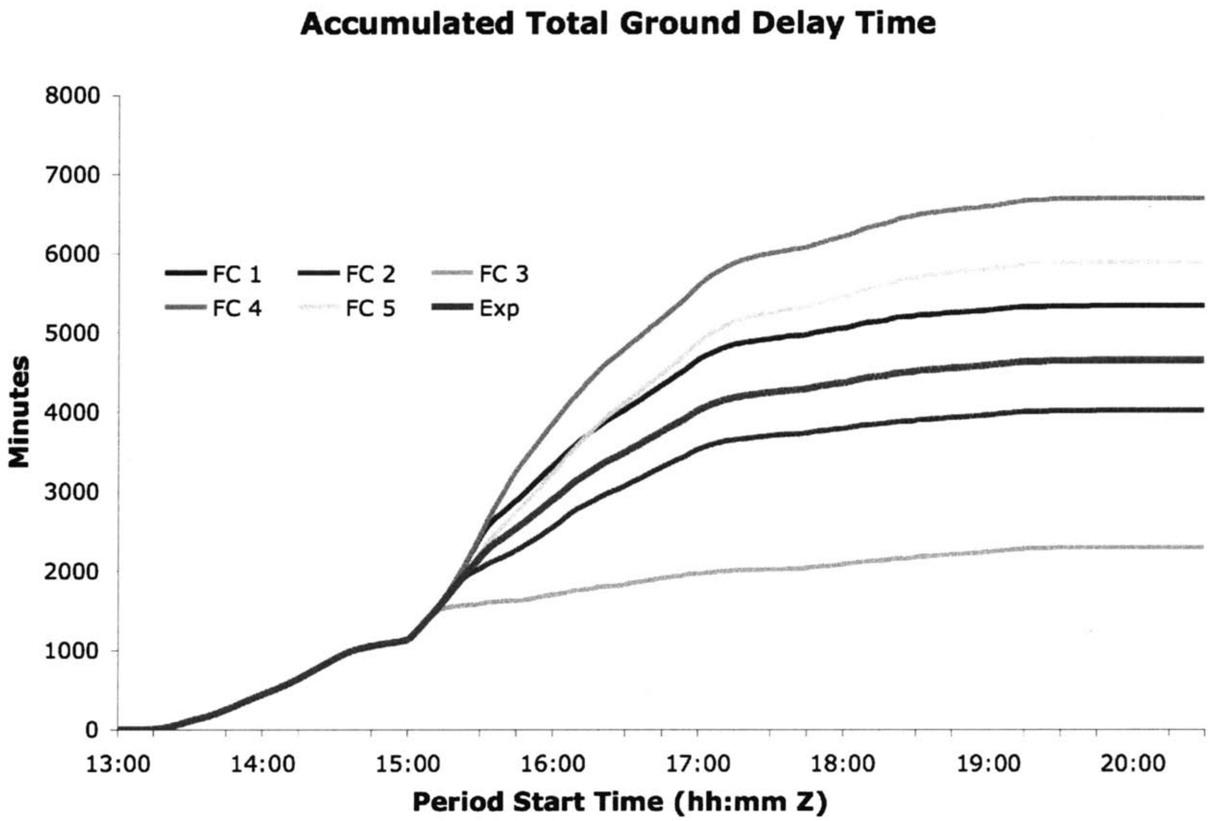


Figure A1D-1: Accumulation of ground delay over time for the two-stage model

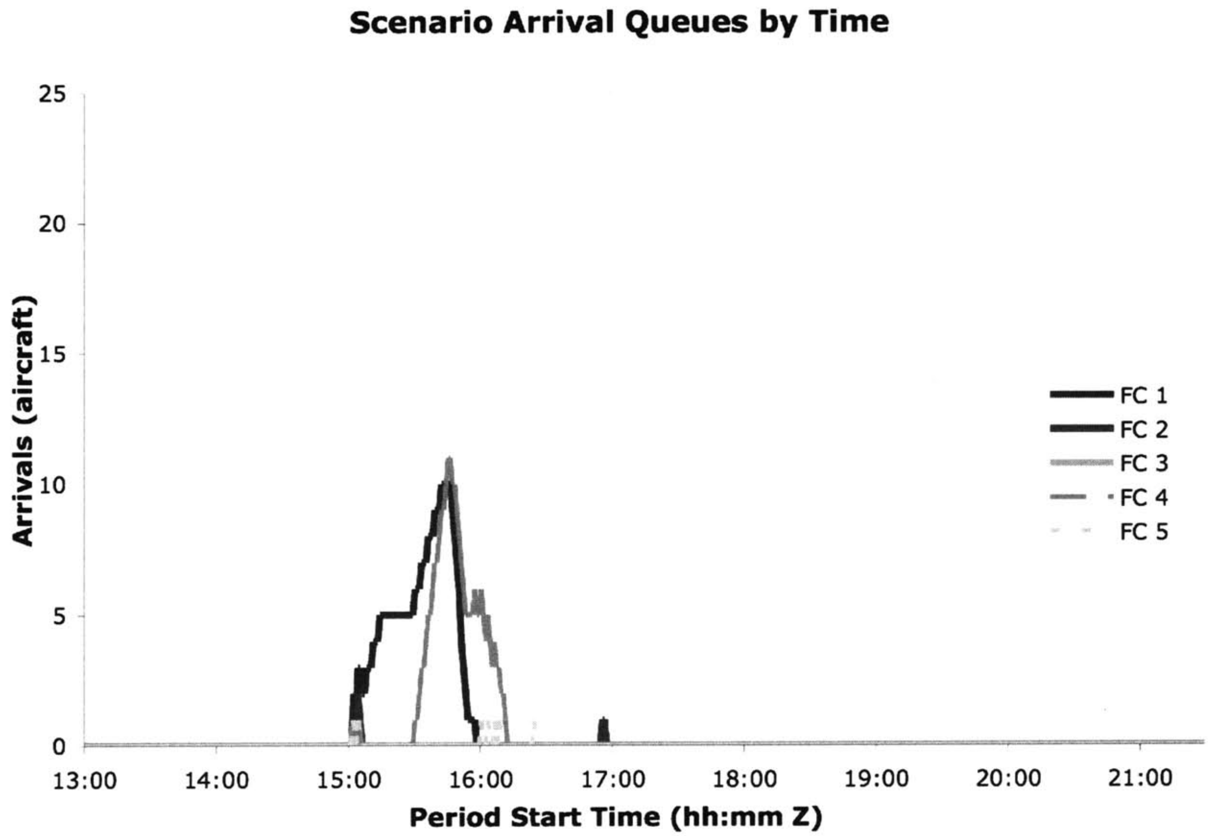


Figure A1D-2: Arrival queue size in aircraft for the two-stage model

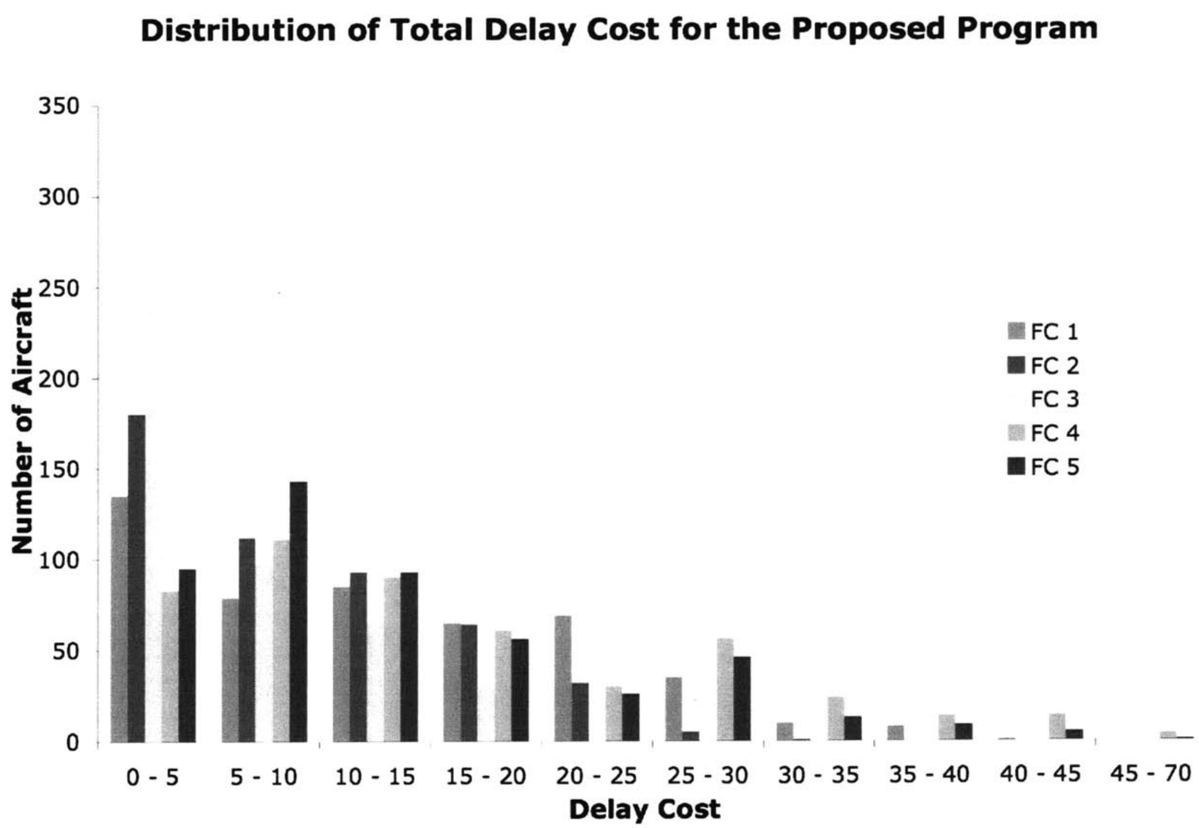


Figure A1D-3: Histogram of delay cost by flight for the two-stage model

Appendix 2: Screen Images of the Tool as Implemented in MS Excel

Many of the figures in this thesis, including the graphs and embedded tables, are direct outputs as taken from the tool. Appendix 2 contains more examples of the Excel-based implementation of the tool. Figure A2-1 shows how the tool tracks demand and cumulative demand of both exempt and included aircraft during over time.

◇	A	B	C	D	E	F	G
1	Slot ID	Slot Time	Scd Dem	Scd Cum Dem	NC Dem	NC Cum Dem	Δ Scd Dem
116	115	14:54	0	0	0	0	0
117	116	14:55	0	0	0	0	0
118	117	14:56	0	0	0	0	0
119	118	14:57	0	0	0	0	0
120	119	14:58	0	0	0	0	0
121	120	14:59	0	0	0	0	0
122	121	15:00	1	1	1	1	0
123	122	15:01	0	1	0	1	0
124	123	15:02	2	3	2	3	0
125	124	15:03	0	3	0	3	0
126	125	15:04	3	6	3	6	0
127	126	15:05	0	6	0	6	0
128	127	15:06	0	6	0	6	0
129	128	15:07	1	7	1	7	0
130	129	15:08	1	8	1	8	0
131	130	15:09	1	9	1	9	0
132	131	15:10	1	10	1	10	0
133	132	15:11	1	11	1	11	0
134	133	15:12	1	12	1	12	0
135	134	15:13	1	13	1	13	0
136	135	15:14	1	14	1	14	0
137	136	15:15	1	15	1	15	0
138	137	15:16	1	16	1	16	0
139	138	15:17	1	17	1	17	0
140	139	15:18	1	18	1	18	0
141	140	15:19	1	19	1	19	0
142	141	15:20	1	20	1	20	0
143	142	15:21	1	21	1	21	0

Figure A2-1: Calculation of arrival demand by slot
Slot ID: Slot ID number
Slot Time: HH:MM Z referring to the start time of the slot
Scd Dem: Scheduled arrival demand of aircraft during the slot
Scd Cum Dem: Cumulative scheduled arrival demand of aircraft up to and including the slot
NC Dem: Scheduled arrival demand of exempt aircraft during the slot
NC Cum Dem: Cumulative scheduled arrival demand of exempt aircraft up to and including the slot
Δ Scd Dem: Scheduled arrival demand of included aircraft (none shown)

Figure A2-2 shows how the tool tracks the accumulation of ground delay.

◇	A	B	L	M	N	O	P
1	Slot ID	Slot Time	GDP>	GDP Hold	GDP Tot GD Time	GDP Avoid	GDP Tot Avd Time
2	1	13:00		0	0	0	0
3	2	13:01		0	0	0	0
4	3	13:02		0	0	1	1
5	4	13:03		0	0	1	2
6	5	13:04		0	0	2	4
7	6	13:05		0	0	2	6
8	7	13:06		0	0	3	9
9	8	13:07		0	0	5	14
10	9	13:08		0	0	5	19
11	10	13:09		0	0	6	25
12	11	13:10		0	0	6	31
13	12	13:11		0	0	6	37
14	13	13:12		1	1	7	44
15	14	13:13		1	2	8	52
16	15	13:14		2	4	7	59
17	16	13:15		2	6	8	67
18	17	13:16		3	9	9	76
19	18	13:17		5	14	10	86
20	19	13:18		5	19	9	95
21	20	13:19		5	24	10	105
22	21	13:20		6	30	9	114
23	22	13:21		6	36	7	121
24	23	13:22		7	43	8	129
25	24	13:23		8	51	8	137
26	25	13:24		7	58	7	144
27	26	13:25		8	66	7	151
28	27	13:26		9	75	8	159
29	28	13:27		10	85	10	169
[illegible]	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]

Figure A2-2: Calculation of ground delay accumulation by time

Slot ID: Slot ID number

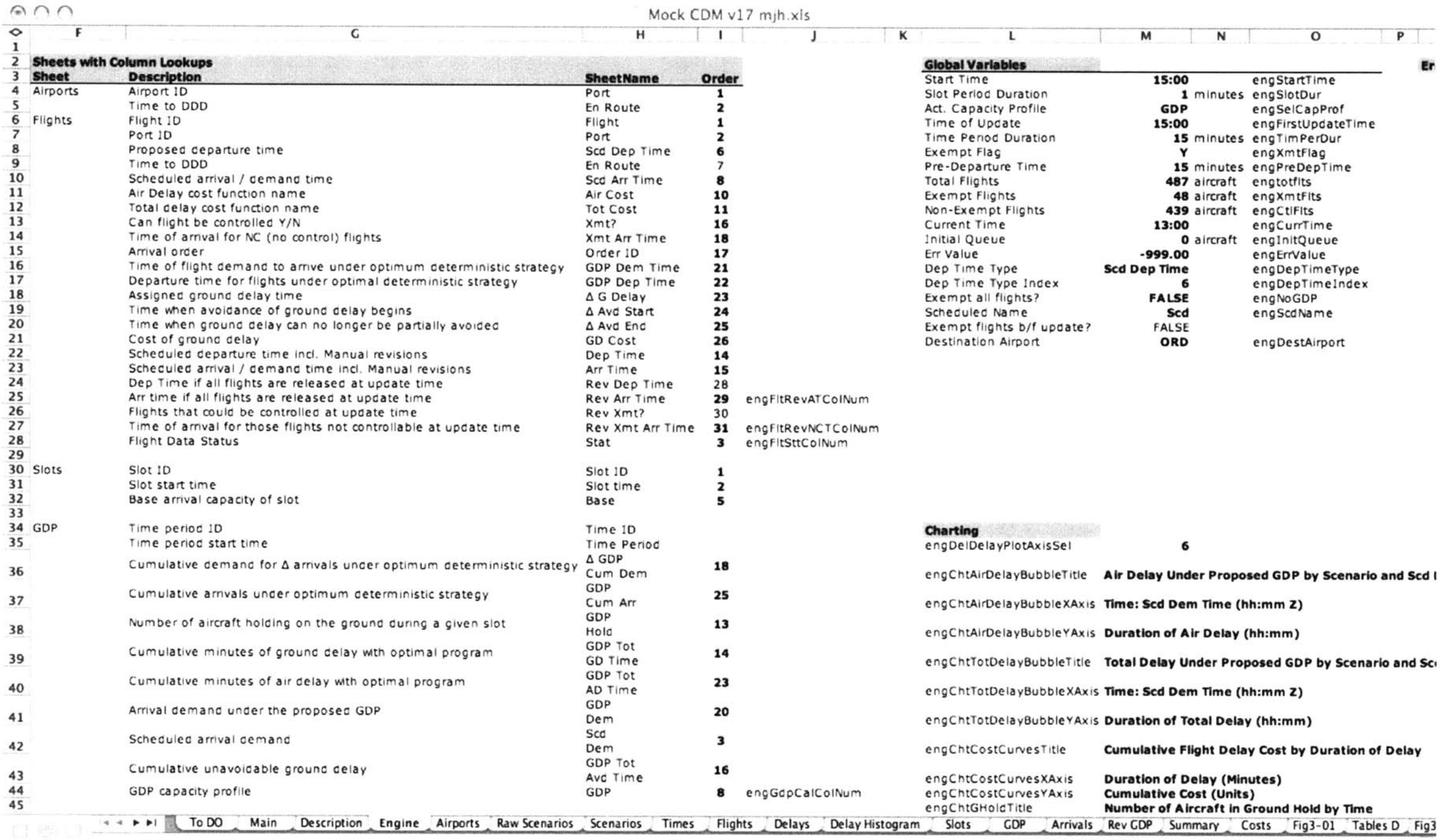
Slot Time: HH:MM Z referring to the start time of the slot

GDP Hold: Number of aircraft in ground hold during slot

GDP Tot GD Time: Cumulative ground delay up to and including slot

GDP Avoid: Number of aircraft in ground hold avoidance (in this example, offset from GDP Hold by 10 minutes)

GDP Tot Avd Time: Cumulative ground delay up to and including slot



Mock CDM v17 mjh.xls

Sheets with Column Lookups

Sheet	Description	SheetName	Order	
Airports	Airport ID	Port	1	
	Time to DDD	En Route	2	
Flights	Flight ID	Flight	1	
	Port ID	Port	2	
	Proposed departure time	Scd Dep Time	6	
	Time to DDD	En Route	7	
	Scheduled arrival / demand time	Scd Arr Time	8	
	Air Delay cost function name	Air Cost	10	
	Total delay cost function name	Tot Cost	11	
	Can flight be controlled Y/N	Xmt?	16	
	Time of arrival for NC (no control) flights	Xmt Arr Time	18	
	Arrival order	Order ID	17	
	Time of flight demand to arrive under optimum deterministic strategy	GDP Dem Time	21	
	Departure time for flights under optimal deterministic strategy	GDP Dep Time	22	
	Assigned ground delay time	Δ G Delay	23	
	Time when avoidance of ground delay begins	Δ Avd Start	24	
	Time when ground delay can no longer be partially avoided	Δ Avd End	25	
	Cost of ground delay	GD Cost	26	
	Scheduled departure time incl. Manual revisions	Dep Time	14	
	Scheduled arrival / demand time incl. Manual revisions	Arr Time	15	
	Dep Time if all flights are released at update time	Rev Dep Time	28	
	Arr time if all flights are released at update time	Rev Arr Time	29	engFltRevATColNum
	Flights that could be controlled at update time	Rev Xmt?	30	
	Time of arrival for those flights not controllable at update time	Rev Xmt Arr Time	31	engFltRevNCTColNum
	Flight Data Status	Stat	3	engFltSttColNum
Slots	Slot ID	Slot ID	1	
	Slot start time	Slot time	2	
	Base arrival capacity of slot	Base	5	
GDP	Time period ID	Time ID		
	Time period start time	Time Period		
	Cumulative demand for Δ arrivals under optimum deterministic strategy	Δ GDP Cum Dem	18	
	Cumulative arrivals under optimum deterministic strategy	GDP Cum Arr	25	
	Number of aircraft holding on the ground during a given slot	GDP Hold	13	
	Cumulative minutes of ground delay with optimal program	GDP Tot GD Time	14	
	Cumulative minutes of air delay with optimal program	GDP Tot AD Time	23	
	Arrival demand under the proposed GDP	GDP Dem	20	
	Scheduled arrival demand	Scd Dem	3	
	Cumulative unavoidable ground delay	GDP Tot Avd Time	16	
	GDP capacity profile	GDP	8	engGdpCalColNum

Global Variables

Start Time	15:00		engStartTime
Slot Period Duration	1	minutes	engSlotDur
Act. Capacity Profile	GDP		engSelCapProf
Time of Update	15:00		engFirstUpdateTime
Time Period Duration	15	minutes	engTimPerDur
Exempt Flag	Y		engXmtFlag
Pre-Departure Time	15	minutes	engPreDepTime
Total Flights	487	aircraft	engtotflts
Exempt Flights	48	aircraft	engXmtFlts
Non-Exempt Flights	439	aircraft	engCtlFlts
Current Time	13:00		engCurrTime
Initial Queue	0	aircraft	engInitQueue
Err Value	-999.00		engErrValue
Dep Time Type	Scd Dep Time		engDepTimeType
Dep Time Type Index	6		engDepTimeIndex
Exempt all flights?	FALSE		engNoGDP
Scheduled Name	Scd		engScdName
Exempt flights b/f update?	FALSE		
Destination Airport	ORD		engDestAirport

Charting

engDelDelayPlotAxisSel	6
engChtAirDelayBubbleTitle	Air Delay Under Proposed GDP by Scenario and Scd I
engChtAirDelayBubbleXAxis	Time: Scd Dem Time (hh:mm Z)
engChtAirDelayBubbleYAxis	Duration of Air Delay (hh:mm)
engChtTotDelayBubbleTitle	Total Delay Under Proposed GDP by Scenario and Sc
engChtTotDelayBubbleXAxis	Time: Scd Dem Time (hh:mm Z)
engChtTotDelayBubbleYAxis	Duration of Total Delay (hh:mm)
engChtCostCurvesTitle	Cumulative Flight Delay Cost by Duration of Delay
engChtCostCurvesXAxis	Duration of Delay (Minutes)
engChtCostCurvesYAxis	Cumulative Cost (Units)
engChtGHoldTitle	Number of Aircraft in Ground Hold by Time

To DO | Main | Description | Engine | Airports | Raw Scenarios | Scenarios | Times | Flights | Delays | Delay Histogram | Slots | GDP | Arrivals | Rev GDP | Summary | Costs | Fig3-01 | Tables D | Fig3

Figure A2-3: Various fields used to control the performance and output of the tool

Appendix 3A: Acronyms

AAR: (Actual) Arrival Acceptance Rate (p. 30)

ACID: AirCraft IDentifier (p. 49)

ADC: Air Delay Cost (p. 89)

ARTCC: Air Route Traffic Control Center (p. 18)

ATC: Air Traffic Control (p. 18)

ATCSCC: Air Traffic Control System Command Center (p. 18)

ATFM: Air Traffic Flow Management (p. 18)

ATM: Air Traffic Management (p. 18)

CDM: Collaborative Decision Making (p. 29)

ERTA: Estimated Runway Time of Arrival (p. 32)

ETA: Estimated Time of Arrival (p. 38)

ETD: Estimated Time of Departure (p. 49)

ETMS: Enhanced Traffic Management System (p. 32)

FAA: Federal Aviation Administration (p. 17)

FAAR: Forecasted Arrival Acceptance Rate (p. 50)

FC #: Forecasted Capacity profile index number # (p. 36)

FCFS: First Come, First Served (p. 19)

FSM: Flight Schedule Monitor (p. 36)

GA: General Aviation (p. 33)

GDC: Ground Delay Cost (p. 89)

GDP: Ground Delay Program (p. 17)

GTA: (Actual) Gate Time of Arrival (p. 32)

GTD: (Actual) Gate Time of Departure (p. 32)

HHI: Herfindahl-Hirschman Index (p. 77)

IFR: Instrument Flight Rules (p.33)

MIT: Miles-In-Trail (Restrictions) (p. 25)

MSL: Mean Sea Level (p. 33)

NAS: National Air Space (p. 17)

OAG: Official Airline Guide (p.33)

ORD: Chicago O'Hare International Airport (p. 49)

PAAR: Planned Arrival Acceptance Rate (p. 36)

RBS/RBS++: Ration by Schedule (p. 38)

RTA: (Actual) Runway Time of Arrival (p. 32)

SAGHP: Single Airport Ground Holding Problem (p. 104)

SFO: San Francisco International Airport (p. 44)

TDC: Total Delay Cost

TM: Traffic Manager (p. 18)

TMI: Traffic Management Initiative (p. 30)

TMU: Traffic Management Unit (p. 18)

TRACON: Terminal Radar Approach CONtrol facility

VFR: Visual Flight Rules

XDC: General Delay Cost (p. 89)

Appendix 3B: Glossary

Active GDP: A ground delay program that is being used to assign delay to flights that have yet to depart

Arrival Acceptance Rate: Arrival capacity of aircraft at an airport per unit of time

Arrival Capacity: The maximum number of flights that can land at an airport during a specified period of time

Arrival Delay: Delay of aircraft in the air before arrival due to insufficient arrival capacity at the destination airport

Arrival Demand: When an aircraft reaches the terminal airspace of the destination airport and either requests permission to land or is directed to an airborne arrival queue

Avoidance Time: The time at which a particular period of delay can no longer be avoided by action of the traffic manager

Capacity Profile: The arrival capacity of an airport over time

Capacity Scenario: A set of mutually exclusive, collective exhausted capacity profiles and associated likelihoods that represent the arrival capacity of an airport

Capacity Scenario Tree: A tree of capacity scenarios states, which indicate how a given capacity scenario may change over time

Controlled flight: A flight that is currently being held on the ground by air traffic control as part of a ground delay program

Demand Time: The time at which a flight requests to land at an airport

Departure Time: The time at which a flight departs from the departure airport

Diversion: A flight that, while en route or in a stack, changes its destination airport because it may run out of fuel before being able to land at the original destination

Drift: The deviation of a flight from its scheduled demand time due to en route atmospheric conditions

End Time: The time after which scheduled flight arrivals are no longer subject to the arrival rates restrictions of a GDP

File Time (Flight Plan): The time at which a flight plan is given to the FAA

File Time (GDP):	The time at which the TM implements a proposed GDP
Popup:	A flight not contained in the OAG for which a flight plan is filed after the implementation of a ground delay program
Proposed GDP:	A ground delay program that has been proposed by a traffic manager and is being evaluated for possible implementation
Stack:	An airborne, FCFS queue for aircraft that have requested to land at a congested airport
Start Time:	The time of the first slot created by a GDP
Terminal Airspace:	The volume of air immediately above and adjacent to an airport used for airborne queuing and final arrival approaches of aircraft
Uncertain:	A quantity or outcome that is not explicitly known but which may fall into a range or discrete list of values with an attributed non-zero likelihood of occurring

Appendix 3C: GDP Tradeoffs

Tradeoff	Rule
#1	The sooner an air traffic management response to anticipated delay is implemented, the greater the effect it will have on reducing potential delay costs, but the less information will be available about the true potential for congestion.
#2	If a GDP undercontrols and does not delay enough flights on the ground, it will be ineffective at preventing future airborne delays; if it overcontrols, flights will be delayed more than was necessary and runway capacity at the destination may go unused.
#3	The sooner a GDP is implemented, the greater the ability it will have to prevent airborne delays, but the more likely that the available information will result in a program that over or undercontrols.
Summary	A ground delay program trades the uncertainty of airborne delays in the future for the certainty of ground delays in the present.
#4	Increasing a PAAR increases the amount of ground delay assigned by a program, decreasing the rate reduces assigned ground delay.
#5	Moving up the start time of a program allows additional flights to be included based on their scheduled arrival times, delaying the start time exempts flights.
#6	Moving up the file time of a program allows additional flights to be included based on their scheduled departure times, delaying the start time exempts flights.
#7	Exempting all or some of the flights originating at a specified airport(s) reduces the number of flights that can be controlled.
#8	Using origination-based or time-based inputs to a ground delay program to exempt long distance flights allows a traffic manager to delay the effects of a program until a later time when more information may be available, but places the burden of delays on a reduced set of shorter flights.

Figure A3-1: A summary of the tradeoffs of a GDP

Appendix 4: Bibliography and Sources

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